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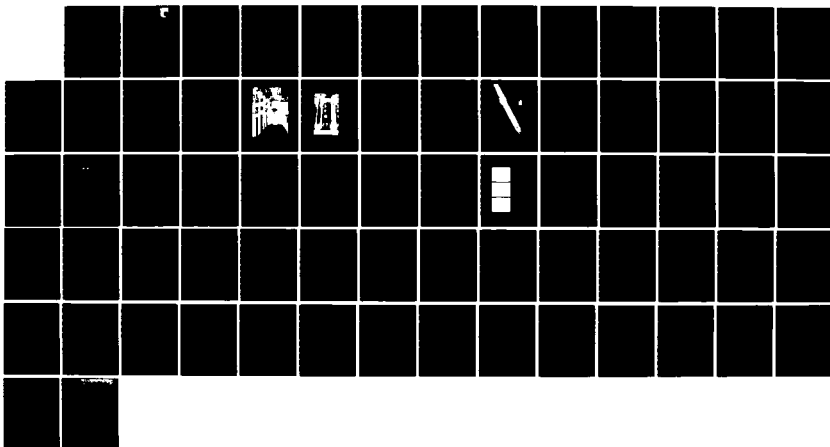
PROCEDURES FOR TESTING AND EVALUATING SPACECRAFT-TYPE
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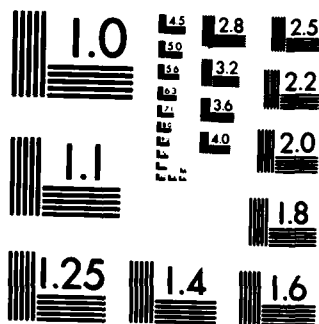
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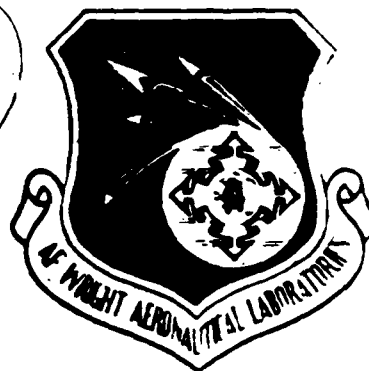


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PROCEDURES FOR TESTING AND EVALUATING SPACECRAFT-TYPE HEAT PIPES

Leonard K. Tower
Warner B. Kaufman

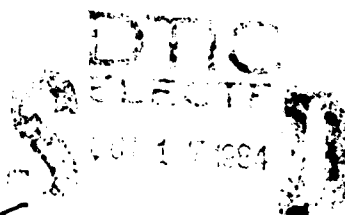
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Fairview Park, OH 44126

April 1984

Interim Report for Period August 83 - December 83

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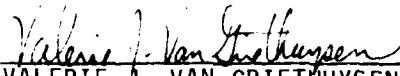
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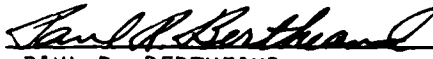
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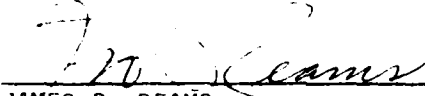
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10	03			
19. ABSTRACT (Continue on reverse if necessary and identify by block number) This report describes part of an effort to develop dependable, cost effective spacecraft thermal control heat pipes. In the program the reliability and performance of 30 commercially available heat pipes were assessed. The pipes comprised 10 groups of varying design, with aluminum and stainless steel as structural materials, and methanol and ammonia as working fluids. The factors studied were noncondensable gas accumulation and heat transfer capability in one "g". Some results in this program, initiated by Lewis Research Center of NASA, were published earlier. The present report, sponsored by AFWAL, supplements the brief earlier report by describing in detail the procedures required to conduct a comprehensive evaluation of heat pipes for thermal control. It discusses the test facilities and testing procedures. The manner in which data may be taken for estimating useful life and comparing performance is described. Some of the pitfalls in making such judgments are illustrated.				
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FOREWORD

The information in this report was assembled for the University of Dayton as Task 20 of Contract No. F33615-81-C-2012 with the Air Force Wright Aeronautical Laboratories/Aero Propulsion Laboratory, of the Aeronautical Systems Division, Air Force Systems Command.

Ms. V. J. Van Griethuysen of the Energy Conversion Branch at the Aero Propulsion Laboratory (AFWAL-POOC) served as Project Engineer. The work was in support of Project 31451949, Thermal Energy Storage, Heat Pipes, and Heat Transfer Investigation.

The report was prepared by Leonard K. Tower and Warner B. Kaufman, principal investigators. As members of the Chemical Systems Branch, Space Propulsion and Power Division of NASA Lewis Research Center, these investigators had previously conducted and reported a life test evaluation of spacecraft thermal control heat pipes. The present report represents part of a program to transfer space heat pipe technology from NASA LeRC to Aero Propulsion Laboratory. In it, the test facilities, instrumentation, test procedures, and data analysis techniques employed in the life test evaluation are described in far more detail than could be reported earlier. This report should provide other experimentalists with the detailed information needed to plan future evaluation programs. The work was performed during the period 10 August to 31 December 1983.

The authors are indebted to the following personnel at NASA LeRC for consultation and assistance in the execution of this work: Dr. Stuart Fordyce, Chief, Space Power Technology Division; Major Alan Willoughby, Air Force Systems Command Liaison Officer; Mr. William Frey, technician, and Mr. Robert Penkava, mechanic, associated with the life test evaluations conducted at the NASA Lewis Research Center.

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SECTION I INTRODUCTION

The aerospace community has for some time pursued the development of reliable, cost-effective heat pipes for spacecraft thermal control. Lewis Research Center of NASA, participating in this effort, conducted a program from 1974 to 1981 to assess the reliability and performance of commercially available spacecraft thermal control heat pipes. The pipes were intended to operate in the neighborhood of 30° C. The types of pipes and their manufacturing sources reflected the variety of fabrication and processing procedures in a survey commissioned by Goddard Space Flight Center of NASA (Reference 1).

The main factors studied in the program were the heat transport capability in one "g" and the noncondensable gas evolved in corrosive reactions between the working fluid and the heat pipe structure. Noncondensable gas evolution, which can occur with working fluids that are compounds, reduces heat pipe performance and useful life (References 2, 3, 4, 5, and 6). The information generated in the Lewis program was intended to facilitate decisions as to processing procedures required for adequate life by providing laboratory experience on the types of spacecraft thermal control pipes surveyed in Reference 1. Results of the program through approximately 14,000 hours of testing were reported in Reference 7. The test facilities continued in operation until about 40,000 hours, but no further data were taken or reported.

The present report supplements the information contained in Reference 7. It describes in detail the test facilities and testing procedures. It illustrates also the manner in which the data such as that taken for Reference 7 may be used to compare and evaluate heat pipes, and some of the effects which the observer must learn to recognize and to deal with in making such judgments.

SECTION II

HEAT PIPES, TEST FACILITY, AND TEST PROCEDURE

HEAT PIPES

The thirty heat pipes are listed in ten groups of three pipes each in Table 1. Those of Groups A through G were designated high performance and, based on the price of the pipes tested, would be expected to cost perhaps 30% more to mass produce than those of Groups H, I, and J. The envelope material was either 304 stainless steel or 6061-T6 aluminum.

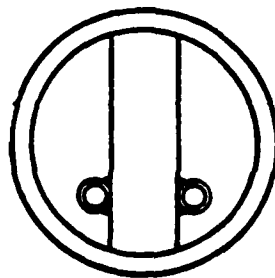
Figure 1 shows the internal configurations. The manufacturer of each configuration is indicated. Configuration I consisted of a slab wick and two arteries. Configuration II used multiple arteries centered by a screen support. Configuration III had an artery of spiralled screen contained in a screen tube and supported by six screen pedestals. Internal parts were 304 stainless steel, except in Configuration II where they were 316 stainless steel. The pipes of Groups H and J had essentially the same internal configuration as those of A and D, but the screen tubes served as reservoirs rather than arteries. The envelope tubes of the above configurations were threaded with fine grooves their entire length. They were 92 cm long with a diameter of 1.27 cm. The pipes of Configuration IV were fabricated by extruding 27 rectangular grooves in the wall. They also were 92 cm long but had an outside diameter of 1.78 cm.

The results of tests on the twenty-one pipes in Groups A through G, reported in Reference 5, will be reviewed briefly. Table 2 shows the noncondensable gas observed in the methanol pipes of Groups A, B, and C. At start-up, no pipes of Group A, one of Group B, and one of Group C gave evidence of gas. Gas was either introduced during processing or more likely was generated on the shelf in the

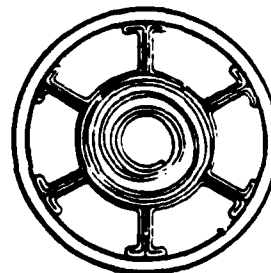
TABLE 1. - INDEX OF HEAT PIPES^a

Heat pipe group	Heat pipe numbers	Internal configuration	Working fluid	Envelope material
A	1,2,3	I	Methanol	Stainless
B	4,5,6	II	Methanol	Stainless
C	7,8,9	III	Methanol	Stainless
D	10,11,12	I	Ammonia	Aluminum
E	13,14,15	II	Ammonia	Aluminum
F	16,17,18	III	Ammonia	Aluminum
G	19,20,21	II	Ammonia	Stainless
H	22,23,24	I	Ammonia	Aluminum
I	25,26,27	IV	Ammonia	Aluminum
J	28,29,30	I	Freon 21	Aluminum

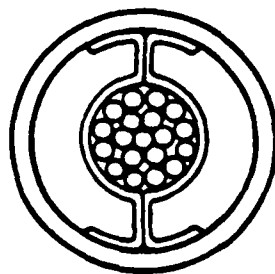
^aAll wick and artery structures were stainless steel.



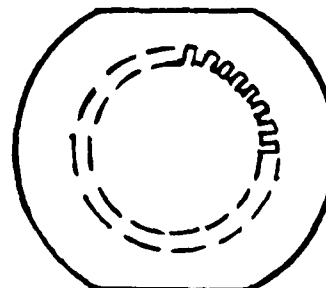
CONFIGURATION I
TRW



CONFIGURATION II
GRUMMAN



CONFIGURATION III
McDONNELL-DOUGLAS



CONFIGURATION IV
DYNATHERM

Figure 1.- Internal Configurations of the Pipes.

23 to 25-month period between manufacture and start-up. At the 4,300-hour level, all pipes of Group C had gas, while at the 12,000-hour level, all pipes in these groups had gas. On the other hand, no pipes of Group A showed any gas to 12,000 hours.

Table 3 presents the noncondensable gas in the ammonia pipes of Groups D, E, F, and G. Of ammonia pipes, those of Group D had the most gas. Pipe 12 was the only one of Group D showing no start-up gas. This pipe was refilled only two weeks before start-up, while its mates were on the shelf about 18 months. This suggests that the gas present at start-up was not introduced in processing. A review of the processing schedules (Reference 5) suggests that intensive cleaning of ammonia-aluminum pipes before assembly may actually exacerbate the process of noncondensable gas formation.

For ammonia pipes, the envelopes of maximum heater power without dryout against evaporator elevation for each group are shown in Figure 2. At a given elevation, no pipe in a group dried out at a power below the corresponding curve for the group. The performance envelope for the pipes of Group G stands alone, while the envelopes for the pipes of Groups D, E, and F are clustered together. Group D is much more sensitive to change in elevation than any other group.

TABLE 2. - NONCONDENSIBLE GAS IN METHANOL HEAT PIPES AT
VARIOUS TIMES

Heat pipe group	Heat pipe number	Gas at start of testing, g mol	Gas at time T_1		Gas at time T_2	
			g mol	T_1 , hr	g mol	T_2 , hr
A	1	0	0	4330	0	12 290
	2	0	0	4330	0	11 856
	3	0	0	4240	0	12 420
B	4	0	(a)	4390	9.0×10^{-5}	12 480
	5	(a)	(a)	4330	10.0×10^{-5}	12 414
	6	0	(a)	4230	7.0×10^{-5}	12 090
C	7	(a)	(a)	4370	3.6×10^{-5}	12 680
	8	0	0	4260	5.2×10^{-5}	11 040
	9	0	0	4230	1.6×10^{-5}	12 290

^a Gas present, amount not determined.

TABLE 3. - NONCONDENSIBLE GAS IN AMMONIA HEAT PIPES AT
VARIOUS TIMES

Heat pipe group	Heat pipe number	Gas at start of testing, g mol	Gas at time T_1		Gas at time T_2	
			g mol	T_1 , hr	g mol	T_2 , hr
D	10	3.8×10^{-4}	7.3×10^{-4}	4 390	10.1×10^{-4}	14 220
	11	6.0×10^{-4}	10.2×10^{-4}	10 100	9.4×10^{-4}	14 280
	12	0	-----	-----	4.4×10^{-4}	12 158
E	13	0	1.7×10^{-4}	10 046	1.3×10^{-4}	14 405
	14	0	0	4 592	0	13 794
	15	0	0	4 600	3.3×10^{-4}	14 136
F	16	0	0	9 880	0	14 347
	17	0	0	9 739	0	14 360
	18	0	0	10 808	0	14 415
G	19	0	0	2 598	0	13 032
	20	0	0	7 919	0	12 587
	21	0	0	9 686	1.5×10^{-4}	14 398

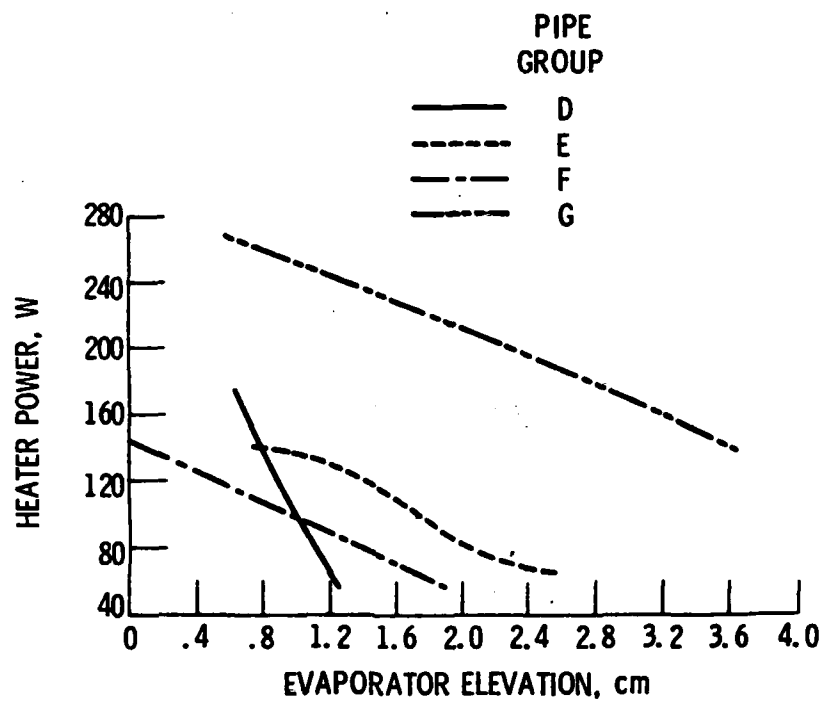


Figure 2. - Envelopes of Maximum Heater Power without Dryout for Ammonia Pipes of Groups D, E, F, and G.

TEST FACILITY

The heat pipe test equipment was divided among three rooms. One room with four test facilities is shown on Figure 3. Each facility consisted of three test stations mounted on two instrument rack cabinets fastened together. Each test station was independent except for sharing a common cooling system and a common vacuum system.

Two test stations are shown in Figure 4. The upper station is complete; the lower one has the vacuum housing removed. The 15 cm diameter housing was evacuated to about 1×10^{-3} torr in order to obtain thermocouple readings free of errors due to convection of room air. The housing flange was sealed to the support disk with an "O" ring. The vacuum feed-thru, located on the back side of the housing, was sealed with an "O" ring also. Beginning at the left on the upper station are the copper inlet and outlet coolant lines and their respective shut-off valves, a vacuum bleed valve, and the vacuum valve. Next are an ammeter, a voltmeter, a power on-off switch with indicating light, and a variable transformer. A log notebook that was kept for each individual pipe may be seen in the center. Just to the right of the notebook is a temperature indicating meter relay which could be set to cut off power to the evaporator heater, if a preset temperature limit was exceeded. The limit switch could be bypassed if desired via the adjacent switch and indicating light. A thermocouple selector switch and its output connector are located to the right. Any one of the nineteen thermocouple outputs could be selected and the temperature read out on a potentiometer. On the far right of the panel is an elapsed hours meter. Below this meter and below the temperature limit meter can be seen two cable connectors. Cables carrying thermocouple outputs, current and voltage and heat pipe identification to a computer and a bargraph oscilloscope from the connectors are not shown.



**Figure 3. – Test Facilities for Twelve Pipes,
Vacuum Housings Removed.**

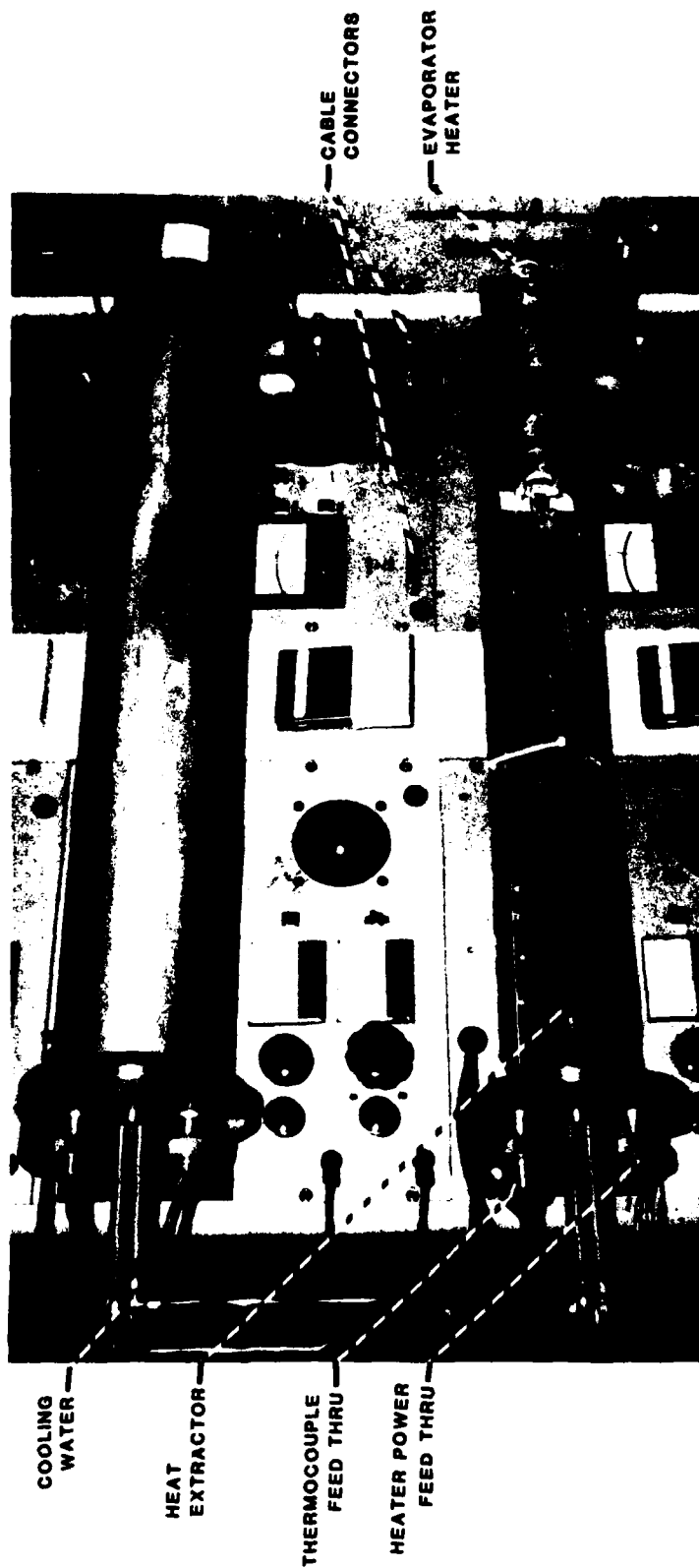


Figure 4. - Two Test Stations, One with Vacuum Housing Installed, the Other with a Pipe in Place and Ready to be Levelled.

An installed heat pipe with heat extractor on the left end and evaporator heater on the right end can be seen in the lower half of Figure 4. The pipe assembly is supported by two bolts, eccentrically adjustable, which are attached to the support beam. The beam is in turn bolted to a support disk which also contains thermocouple, power, and coolant feed-thrus. The coolant lines are brazed to the outboard ends of four stainless steel tubes about 15 cm long. The tubes are sealed to the support disk with "O" rings. The facilities were designed with the intention of testing cryogenic heat pipes eventually. Cryogenic heat pipes would require cryogenic coolant. The long stainless steel tubes were intended to form a heat conduction barrier between the coolant lines and the "O" ring vacuum seals.

The thermocouple leads were sealed with an epoxy cement into individual holes in bakelite disks. The disks were sealed likewise into 2.54 cm stainless steel tubes. The tubes themselves were installed into vacuum feed-thrus brazed into the support disk. The thermocouple leads were terminated internally on a terminal strip attached to the support channel. The electrical leads were run through in a similar manner and terminated at a separate terminal strip also fastened to the support beam.

HEAT EXTRACTOR

In operation, heat was extracted from the heat pipe condenser section by a series of eleven 2.5 cm long brass blocks spaced 0.25 cm apart along four stainless steel coolant tubes. This assembly is shown on the left end of the exposed heat pipe in Figure 4. The extractor was fabricated in two halves which were clamped together on the pipe with bolts top and bottom. The blocks were spaced off the condenser by 0.03 cm thick shrink plastic tubes to provide thermal resistances between the pipe and the brass blocks. The coolant tubes running through the heat

extractors were manifolded together in series so that coolant circulation through them resulted in uniform average sink temperature over the entire length of the condenser. A thermocouple located at the center of each block allowed accurate determination of the temperature. Thus, the location of the front of any noncondensable gas volume accumulated in the condenser end of the pipe could be defined to within the length of one block. Axial thermal conduction along a solid heat extractor would have precluded accurate determination of the gas front.

EVAPORATOR HEATER

The initial evaporator heater was designed to radiate heat from the inside surface of the heater tube to the outside surface of the evaporator section of the heat pipe. This design permitted easy attachment of thermocouples to the heat pipe. Furthermore, it was felt that the absence of a massive heater block would result in more rapid response to dry out.

The heater pictured in the upper right portion of Figure 5 was constructed on a 2.5 cm diameter stainless steel tube 31.8 cm long. First, the tube was plasma sprayed with alumina from end to end to a thickness of about 0.1 cm. Nichrome resistance wire was machine wound over the alumina coating and was prevented from unwinding by securing each end under a stainless steel clamp. The wire ends were terminated under the head of the respective clamp bolts. The clamps were thus electrically insulated from the stainless steel tube by the initial layer of alumina. The wound assembly was then coated from clamp to clamp with a second layer of alumina. The heater was spaced concentrically to the heat pipe evaporator section by an alumina ring (not shown) just inside each end. Electrical leads were connected between two nuts on each clamp bolt. The heater assembly was covered with several

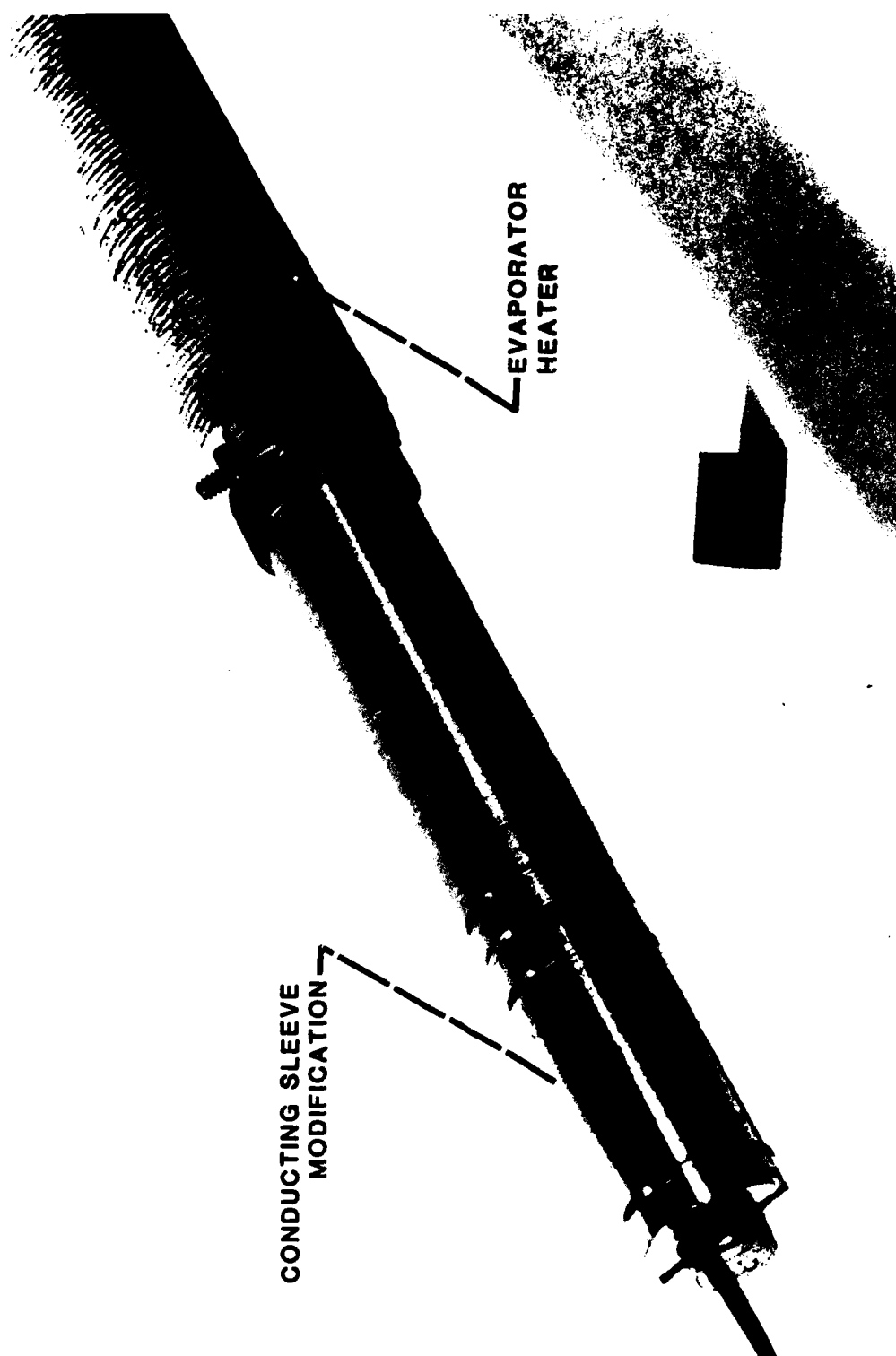


Figure 5. - Evaporator Heater Partially Assembled.

layers of aluminum foil to further reduce radiation heat losses.

This heater, without the conduction sleeve, radiated sufficient heat to the heat pipe. However, it was unsatisfactory for several reasons. When dryout occurred, the over-temperature relay cut out heater power, but the mass of the heater tube and alumina coatings caused heat to continue to be radiated to the dried out region of the evaporator for some time. Also, heat was not supplied uniformly along the length of the evaporator due to heater end losses. In addition, the high operating temperature of the heater caused the thermocouple lead wire insulation to deteriorate rapidly resulting in secondary junctions. Finally, radiation from the heater assembly to the vacuum housing caused concern for the "O" ring vacuum seal in the housing flange. Because of this radiation loss, the actual amount of power input to the evaporator was difficult to determine.

To alleviate these problems, the heater was modified so as to conduct heat to the heat pipe evaporator rather than radiate heat to it. This simple modification, shown on Figure 5, consisted of the addition of an aluminum sleeve that essentially filled the annulus between heater I.D. and heat pipe O.D. The sleeve was comprised of two sections; the forward section was about 5.1 cm long, while the aft section covered the remaining 25.4 cm of evaporator length. The two sections were thermally insulated from each other by a Teflon washer. In this way, dryout of the evaporator end could be quickly recognized. Both sections were split along the horizontal centerline for assembly purposes. An axial groove was cut into the O.D. of the sleeve along the top centerline to accommodate the thermocouple leads. Holes were provided through the sleeves at the thermocouple locations so that the thermocouple leads could contact the heat pipe wall. Circumferential grooves were cut in each end of each section

into which stainless steel wire was wrapped to secure the halves during assembly. Each half was coated with Dow Corning No. 340 Silicone Heat Sink Compound, and the sections secured on the heat pipe evaporator with stainless wire. The assembled sleeve also was coated with grease on the O.D., and the heater carefully drawn over it.

This design provided much more uniform heat input over the evaporator length. The two-inch forward section, separated thermally from the remainder, allowed early detection of evaporator dry out. Since the heater resistance wire, alumina coatings, and stainless steel tube now operated at a much lower temperature, no further problems were encountered with thermocouple leads or vacuum seals. The heat loss from the heater was now so small that thermal power input to the evaporator was considered the same as the electrical power input to the heater. Even though the aluminum sleeve acted as a heat sink, quicker decrease in evaporator temperature could be achieved because of the much lower heater operating temperature. No further problems were encountered with the heaters during the lifetime of the tests.

COOLING SYSTEM

A recirculating cooling system supplied cooling water to seven facilities (twenty-one heat pipes) at about 40°C. A recirculating system was used for two reasons: one, to more accurately control temperature, and, two, to prevent clogging of small openings and tubes by reducing mineral intake. A schematic drawing of the system is shown in Figure 6. Thermostatic switches F_1 , F_2 , F_3 controlled power to the units indicated in the table. F_1 , F_2 , F_3 were set to open or close contacts at the temperatures indicated by the set point indicating arms on the temperature controller. The movable pointer indicated

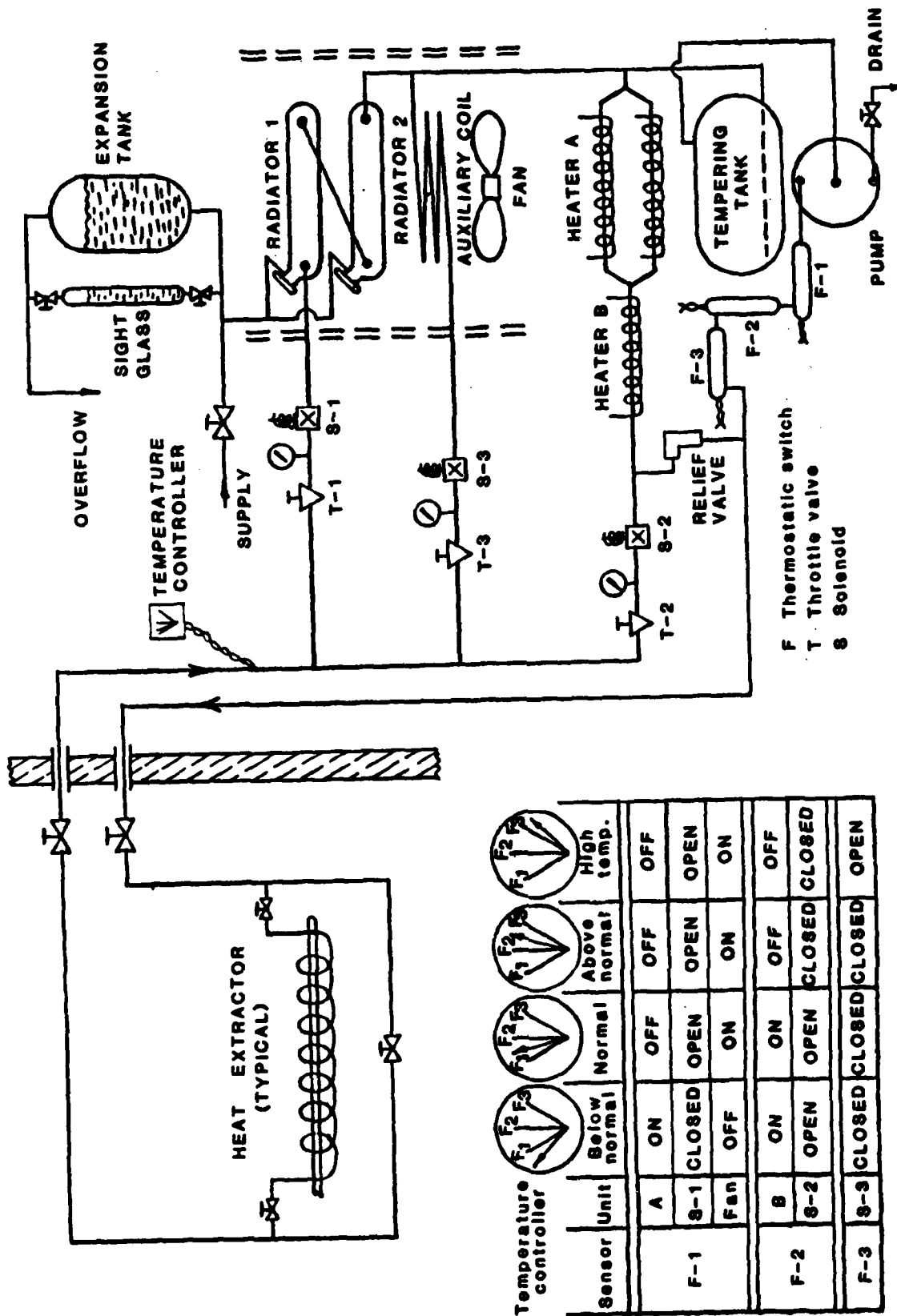


Figure 6. - Circulating Cooling System Schematic.

the temperature sensed by a thermocouple on the coolant supply manifold. For instance, if the temperature in the manifold fell below that indicated on the meter by arm F_1 , heaters A and B were both turned on and coolant flow was directed past the two heaters by solenoid valve S-2. Thus, all heating available was being applied and all cooling was bypassed. In the event of high temperature indicated in the manifold, all heating was turned off, and all available cooling was applied by closing S-2 and opening solenoid valves S-1 and S-3. At normal operating temperature, the coolant flow was divided between cooling radiators and the small heater B. However, excursions higher or lower than the "normal" range were very seldom encountered during 14,000 hours of test operation. The throttle valves T-1, T-2, and T-2 were set during initial start-up and no further adjustments were required. Pipes in Groups H, I, and J were serviced by a system that circulated coolant from a commercially available laboratory thermal bath which maintained about 40°C coolant temperature.

THERMOCOUPLE INSTALLATION

A total of nineteen iron-constantan thermocouples of 30 gauge wire were installed on each pipe. All were attached along the top of the pipes at locations indicated in Figure 7. Couples 1 and 1A were located in the forward short section of the evaporator heater sleeve. Couple 1A was connected to the temperature indicating meter relay that tripped off electrical power to the heater at a preset temperature. Couple number 10, in the adiabatic section of the pipe, was used to indicate the true pipe vapor temperature, since there should be no evaporation nor condensation in this section. Couples 14 through 24 were located near the center of each block in the heat extractor.

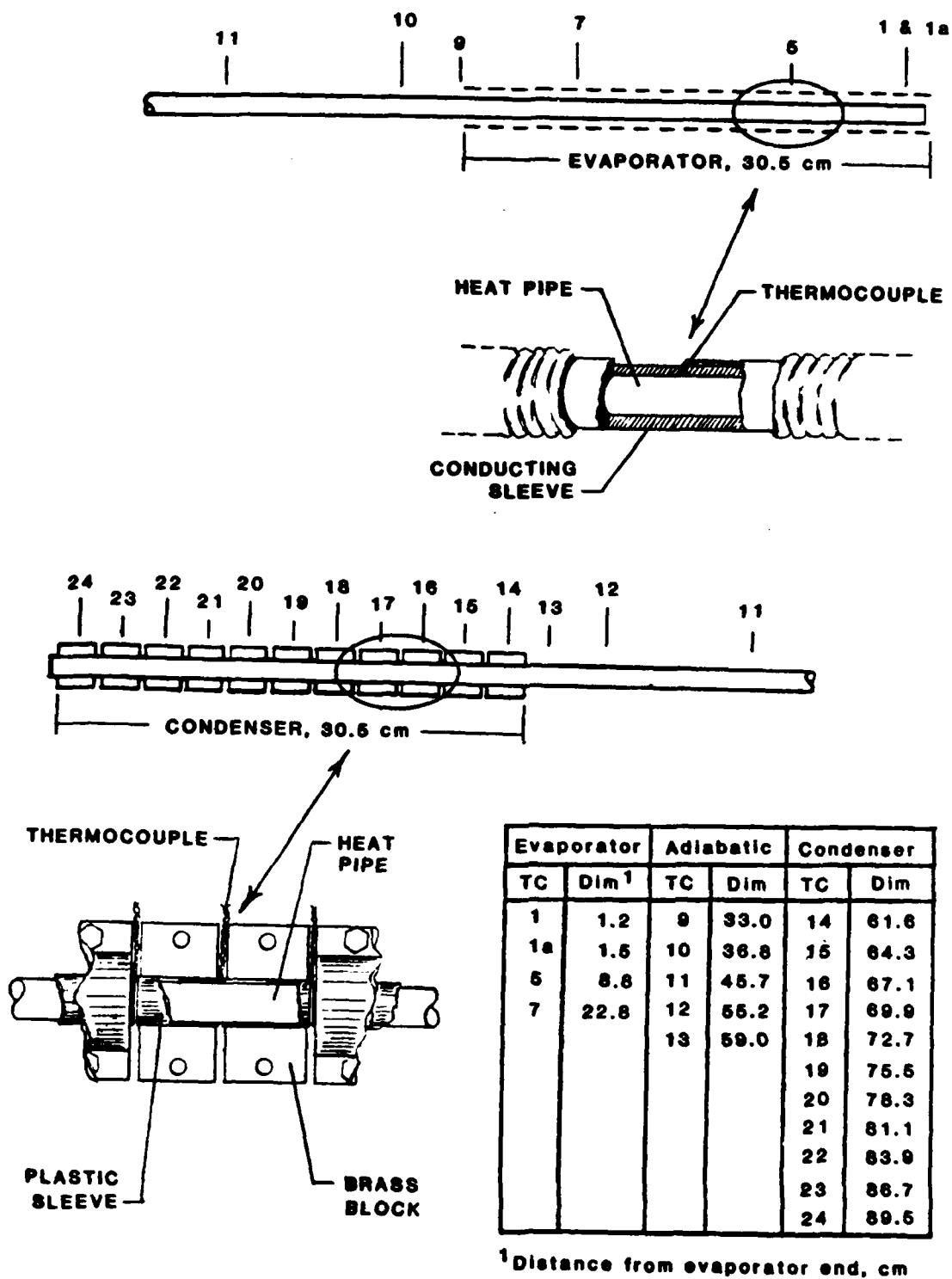
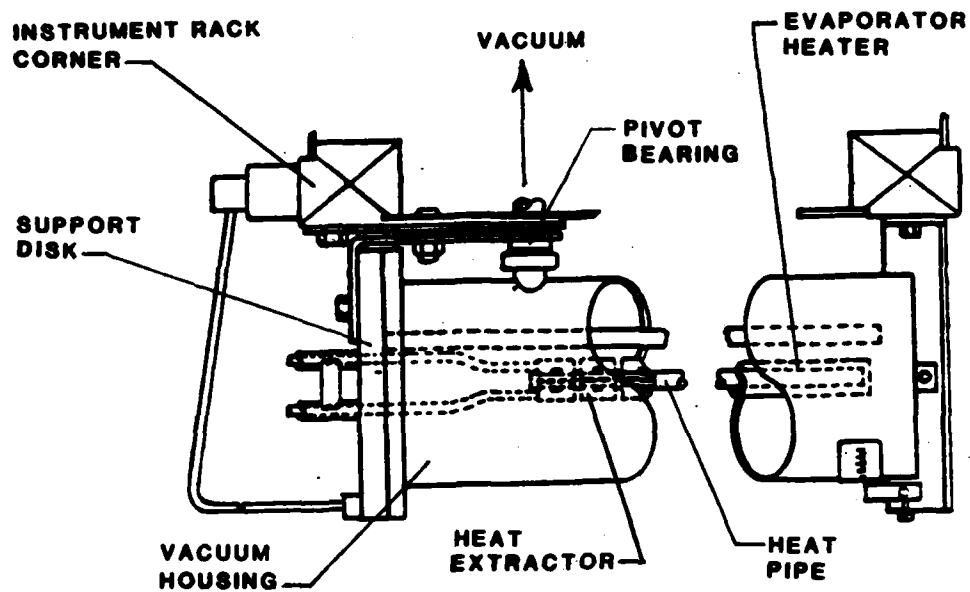


Figure 7. - Thermocouple Locations on Heat Pipes.

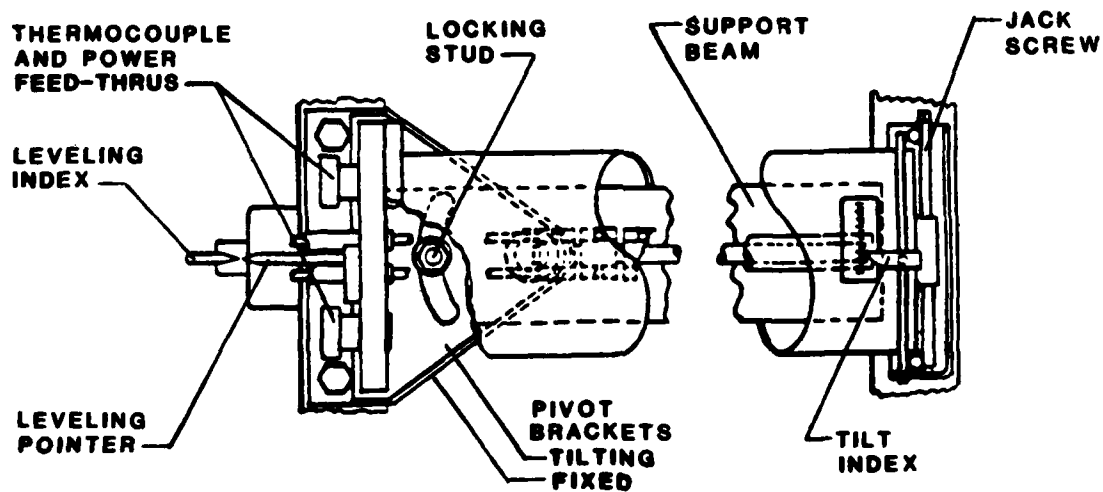
The thermocouple beads were attached to the stainless steel heat pipes by spot welding. In the case of the aluminum heat pipes, the couples were first attached with an epoxy cement. This method was very unsatisfactory. Some couples lifted off the pipe wall along with the epoxy. Others stayed attached, but the beads apparently floated up out of contact with the pipe before the epoxy set up completely, thereby creating a thermal barrier of epoxy. The resulting temperature indications were inaccurate and inconsistent. An attempt was made to hold the beads against the pipe while the epoxy hardened by covering the bead and epoxy with a strip of aluminum foil wrapped with wire. An improvement was observed, but some inconsistency was still evident. Finally, a thermally conducting (Eccobond 285) epoxy was found. While the epoxy dried, the bead was held against the pipe with narrow strips of adhesive-backed aluminum tape. Verification of thermal contact was made by checking the electrical continuity between a thermocouple lead and the pipe. The thermocouple beads in the evaporator heater, Figure 7, inserted into the holes in the sleeve until they contacted the evaporator, were then cemented with epoxy. The inset at the bottom left shows a thermocouple attached under the plastic sleeve with the front halves of two heat extractor blocks removed.

HEAT PIPE INSTALLATION

Figure 8 shows details of the pipe levelling and tilting arrangements. After the thermocouples and evaporator heater were assembled on a pipe, the condenser end was clamped into the heat extractor which had previously been assembled into the support disk. The pipe was located so that the pivot point coincided with the horizontal centerline at the end of the condenser. Later in the installation procedure, the tilt index pointer was



(a) Top view



(b) Side view

Figure 8. - Test Station Showing Components for Leveling and Tilt Indexing.

positioned over the horizontal centerline of the evaporator end of the heat pipe. Therefore, any elevation of the evaporator end, positive or negative, was referenced to the condenser end. The two bolts supporting the heat pipe on the support beam were eccentrically adjustable so that the pipe could be aligned with the centerline of the support beam. The thermocouple leads and the electrical leads were then connected to their respective terminal strips.

A support disk, Figure 8, was bolted to a steel bracket which pivoted on the 3.2 cm diameter vacuum connection. The bracket could be locked in any angular position to a second bracket which was fixed to the corner of the instrument cabinet. A small level was placed in a vee groove on the top side of a metal block. A vee groove in the bottom side of the block permitted it to set between thermocouples near midpoint of the heat pipe. The locking stud nut on the pivot bracket was loosened, and the whole assembly, support disk with attached support beam, and the heat pipe, was rotated around the vacuum connection until the bubble in the level indicated the heat pipe was in a level position. The locking stud nut was tightened and the level again checked. The levelling index, held in a magnetic base positioned on the side of the instrument rack, was adjusted until it was aligned with the levelling pointer temporarily attached to the support disk at its horizontal centerline.

The vacuum housing was then carefully drawn over the heat pipe and its support assembly so as not to disturb the level setting. The vacuum connection to the housing was completed, and the housing flange was clamped to the support disk with three C clamps. The location of the levelling pointer relative to the levelling index was then checked. If any movement had occurred, the adjusting stud nut was loosened slightly and the whole assembly, including the vacuum housing, was pivoted until the pointer tip was

realigned with the index tip. The heat pipe itself was then assumed to be in level position.

A jackscrew was threaded through a block fastened to the closed end of the vacuum housing. It was adjusted until the bottom end just contacted a bracket affixed to the instrument rack thereby supporting this end of the housing. A pointer was fastened to the same bracket. This pointer was now adjusted to the "0" index on a scaled label fixed to the vacuum housing at a point corresponding to the location of the evaporator end of the heat pipe. The label was marked in 0.32 cm (1/8 inch) increments to ± 3.8 cm (1-1/2 inches). The locking stud nut in the pivot bracket was now loosened slightly so that the evaporator end of the assembly could be raised or lowered via the jackscrew. Vacuum was established in the vacuum housing and the pipe was ready to be started.

STEADY-STATE LIFE TESTING

The pipes were designed to operate around 30°C. The tests described herein were intended to accelerate the generation of gas, therefore, the steady-state test temperature was set at 60°C. The test temperature for the low performance pipes of Groups H, I, and J was set at 50°C. Each pipe ran continuously at its test temperature except when its status determination was being made. With the pipes tilted evaporator end up at 0.62 cm, power to the evaporator heater was increased slowly until the thermocouple located at T_{10} (adiabatic section) indicated the test temperature had been reached. The power required to maintain this temperature varied from pipe to pipe depending on configuration, quantity of evolved gas, working fluid, and manufacturing variances. The elapsed hours meter was activated when heater power was energized. The temperature indicating meter was set to trip off heater power if thermocouple 1A reached 75°C.

PIPE STATUS DETERMINATION

It was originally intended to check each pipe for performance changes and gas quantity at regular intervals. However, due to reductions in personnel and other circumstances, the checks were not made as frequently as desired.

Gas Determination

It was important to determine how much gas, if any, had formed during two years of storage between manufacture and the initial testing. This "shelf" gas was determined as soon as practicable after start-up, generally within the first eight hours. Gas was determined from the pipe temperature profile as discussed in the Appendix. When either performance or gas checks were to be made, the coolant inlet and outlet lines were disconnected at the support disk of the pipe in question. They were replaced by temporary lines from a small portable recirculating system. This system pumped a solution of ethylene glycol and water, controlled to a precise temperature, usually 0°C. To determine the quantity of gas accumulated, the pipe remained at a positive tilt of 0.62 cm, but heater power was reduced to a level just sufficient for the working fluid vapor to drive any noncondensable gas to the condenser end. About ten to fifteen minutes were allowed for the system to reach equilibrium before heater power, tilt, temperature profile, etc., were recorded. Normally, the pipe also was tilted to a negative 0.32 cm to determine if the amount of excess fluid (overflow) was sufficient to affect the temperature profile and thereby the calculated volume of gas. With the evaporator below the condenser, this "puddle" would be evidenced by a depressed temperature at T_1 .

Performance Determination

The initial performance test was made on each pipe to evaluate the heat transport capability; subsequent performance checks were made to observe any degradation of performance with time. The static head to which a pipe will pump at a given power in a gravity environment is indicative of transport capability. While the pipes are not subject to gravity in space applications, checking them in this manner allows comparison of one pipe against another. Furthermore, it also gives an indication of sensitivity to accelerative disturbances such as spacecraft engine restart. The maximum static head was taken as the elevation reached just before the evaporator indicated dryout. For this determination, the evaporator end was raised in steps, usually of 0.62 cm, until dryout occurred while heater power and pipe temperature level were maintained constant. A second method was simply to increase the heater power, in steps, while maintaining the elevation and pipe temperature constant. The power attained just before evaporator dryout was considered maximum heat transport capability at the specified elevation. Both methods were used and, as in the case of the gas check tests, time was allowed for equilibrium to occur before data were recorded.

SECTION III

PROCEDURES FOR DATA ACQUISITION AND ANALYSIS

DATA SYSTEM

The data system consisted of these major components, all manufactured by Hewlett-Packard Company: 9810A Calculator, 3480C Digital Voltmeter with 3485A Scanner, 9865A Cassette Memory, and 9862A Plotter. Further discussion of the hardware appears in the Appendix. Operation of the system software is described here in more detail for the following reasons: First, retrieval or re-examination of any data taken on the former Lewis facilities requires that the cassette tapes containing the data be accessed by the software previously used for this purpose. Second, the data-taking functions prepared for the Lewis facility have proven to be extremely useful. They could readily be implemented on newer systems where voluminous heat pipe data are to be acquired. Third, any resumption of life testing on the low-temperature heat pipes employed in the Lewis program might be facilitated by using the same data tapes and storage format employed previously.

DATA ACQUISITION

Because of calculator memory limitations, a single program could not be used to take, and to plot and analyze data. The Take Data program was, therefore, designed to take and store data on tape cassettes for subsequent plotting and computation. The data-taking function was initiated by positioning the roll-around cart containing the data system in front of the heat pipe to be tested. The cables connecting the scanner to voltages from the heat pipe were plugged into connectors on the heat pipe rack. The Take Data program was entered into the calculator from magnetic cards or from a cassette recorder tape. A cassette tape previously marked into files was inserted in

the tape recorder, and data taking commenced. More detailed information on the Take-Data program and its functions can be found in the Appendix.

VIDEO BARGRAPH PHOTO RECORD

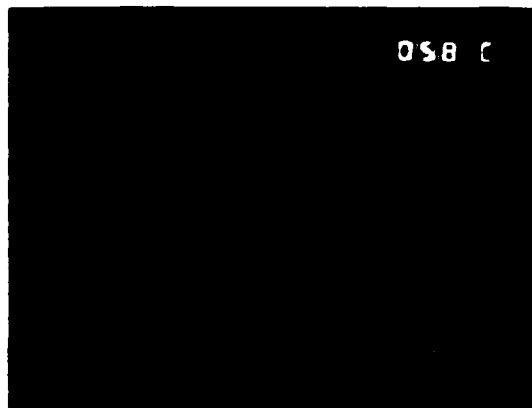
A continuous visual indication of the temperatures on the heat pipe being observed was given by a video bargraph, known as "Metrascope." This device gave a simultaneous bargraph display of all the thermocouples that were in actual use. It was in parallel with the voltmeter/scanner unit. A quick visual indication of heat pipe behavior and problems was available to the operator in order to facilitate data taking. The readings were not used as part of the data record. However, as a routine part of the test procedure, a black and white instant photograph was taken of the video display each time data was taken for recording. Some typical photographs of the video bargraph display are shown in Figure 9.

DATA RETRIEVAL, PLOTTING AND COMPUTATION

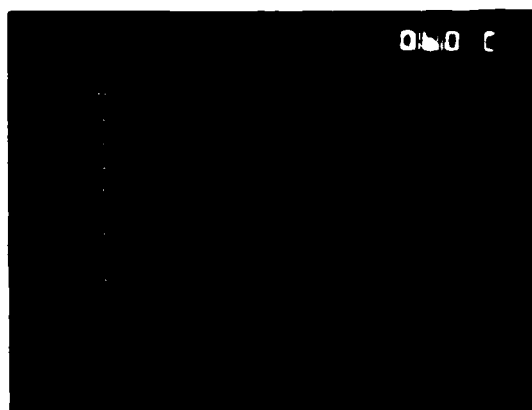
Data stored on the cassette tapes were retrieved and plotted by the Plot-Data programs. These programs plotted temperature against location along the heat pipe and lettered the plot appropriately upon completion. An extended version of the Plot-Data program, the Gas-Analysis program, also computed the noncondensable gas present in the Lewis ammonia-filled and methanol-filled pipes. Use of the programs is illustrated by a discussion of the Gas-Analysis program in the Appendix.

METHODS OF EVALUATING THE HEAT PIPES FROM DATA

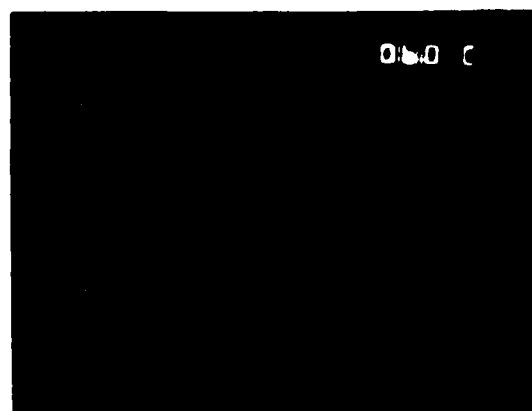
In evaluating the suitability of a heat pipe for any application, two factors must be considered. One of them is the useful life of the pipe compared to the tour of duty anticipated. The other is the performance of the pipes.



**(a) Nongassy Pipe
at Test Conditions.**



**(b) Pipe with
Noncondensable Gas.**



**(c) Onset of
Evaporator Dryout.**

Figure 9. - Video Bargraph Photo Record Displays.

The Lewis spacecraft thermal control heat pipe tests were addressed to both of these factors. Extensive cross plotting and analysis had not been undertaken at the time the results were presented at the Third International Heat Pipe Conference (Reference 7). It was anticipated that a more comprehensive report on the status of these heat pipes would be prepared after further life-testing. Considerable accelerated life-test time accrued after the preparation of Reference 7, but no further data were taken.

In this section, an indication will be given of some comparisons which might be made among pipes in the Lewis program. These comparisons were selected to illustrate the type of information which can be obtained in an evaluation of heat pipes, if an adequate data retrieval system is available.

GAS ACCUMULATION

Noncondensable gas, evolved by working fluid decomposition, is the principal cause of performance degradation with time in spacecraft thermal control heat pipes. The working fluids are generally compounds such as ammonia, methanol, halogenated hydrocarbons, or possibly water, all of which may react with the container or wick structures to produce noncondensable gas. This gas accumulates in the end of the condenser, blocking off heat transfer area. The operating temperature of a heat pipe at a given power level in a given installation is thereby raised. A sufficient increase may represent a heat pipe failure. A variable conductance heat pipe with deliberately introduced non-condensable gas will be less sensitive to the effect of gas resulting from corrosion (Reference 6).

Gas accumulation for 21 of the thermal control heat pipes in the Lewis life-test program are reported in Reference 7. The life tests were accelerated by operating at a temperature of 60°C, somewhat above the normal

temperature of about 30° to 40°C . For methanol stainless steel pipes, equations in Reference 3 enable computation of the increase in gas accumulation at the accelerated testing temperature to be estimated. The test temperature of 60°C will produce about four times as much gas as a steady operating temperature of 30°C , or 2.5 times as much gas as a 40°C operating temperature. For ammonia-aluminum pipes, no simple correlation between temperature and noncondensable gas has been found (Reference 6).

Although Reference 7 presents gas evolution results for heat pipes in the Lewis test program, space did not permit any discussion of comparisons which might be made. Illustrations of some useful comparisons have been selected from data for the 21 heat pipes in the Lewis test program and will be presented here.

The ensuing discussion will concern the behavior of heat pipes under conditions of high thermal load and often pathological behavior. For this reason, Figure 10 is shown here representing normal behavior of a pipe known to be free of gas. The temperatures as indicated by thermocouples in the evaporator, adiabatic section, and condenser are nearly constant. The mean temperatures decline slightly from evaporator to condenser because of heat transfer. The non-uniformity in the condenser may represent a fluctuation due to a hydrodynamic effect, or it may be an instrument error.

Figure 11 presents plots of temperature against distance from the evaporator end of Pipe 10, an ammonia-aluminum pipe, after accumulated testing time of 8; 4,400; 10,100; and 14,200 hours. The heater power was 50 watts for the 8-hour data, and 10 to 12 watts for the other data. The evaporator end was elevated 0.63 cm above the condenser end. The relative amount of gas in each run cannot be deduced directly from the plots of temperature. Therefore, the computed noncondensable gas at the foregoing

test times is printed on the figure. The gas present at 8 hours represents "shelf" gas generated during the approximately two years between manufacture of the pipe and test.

Figure 12 shows the noncondensable gas accumulation against time for Pipe 10 taken from the values printed on Figure 11. A least-mean-squares fit of the data using the equation $n = B\sqrt{t + t_0}$ is also shown, where $B = 7.97 \times 10^{-6}$ and $t_0 = 3961$ hrs. Here, t_0 represents an effective time for creation of "shelf" gas at the accelerated test temperature of 60°C , rather than the actual storage temperature of around 22°C . The fit of such an equation presumes a parabolic time dependence for the corrosion process. Such a relation was found for methanol, stainless pipes (Reference 3). However, erratic life test results for ammonia-aluminum pipes, have precluded the derivation of any useful equation by which gas formation can be predicted from time, temperature, and pipe area (Reference 6). The curve on Figure 12 can, therefore, only be considered as suggestive of a relationship which may sometime be substantiated.

Noncondensable gas data presented to this point were all taken at relatively low power and with the evaporator end at not more than 0.63 cm elevation above the condenser end. High power, in particular, gave temperature profiles very similar to those caused by gas for some heat pipes. Figure 13 shows profiles of temperature against distance for Pipe 10, a gassy pipe, at several high heat powers. The evaporator elevation was about 0.63 cm, and the time was about 12,300 hours. The apparent gas computed from these profiles increases with power. When this apparent gas is plotted against heater power in Figure 14 (a data point at 12 watts and 10,150 hours from Figure 11 is also shown), a nearly linear increase is perceived. The conjecture can be made that as power was increased, the wicking structures in the evaporator were depleted of fluid

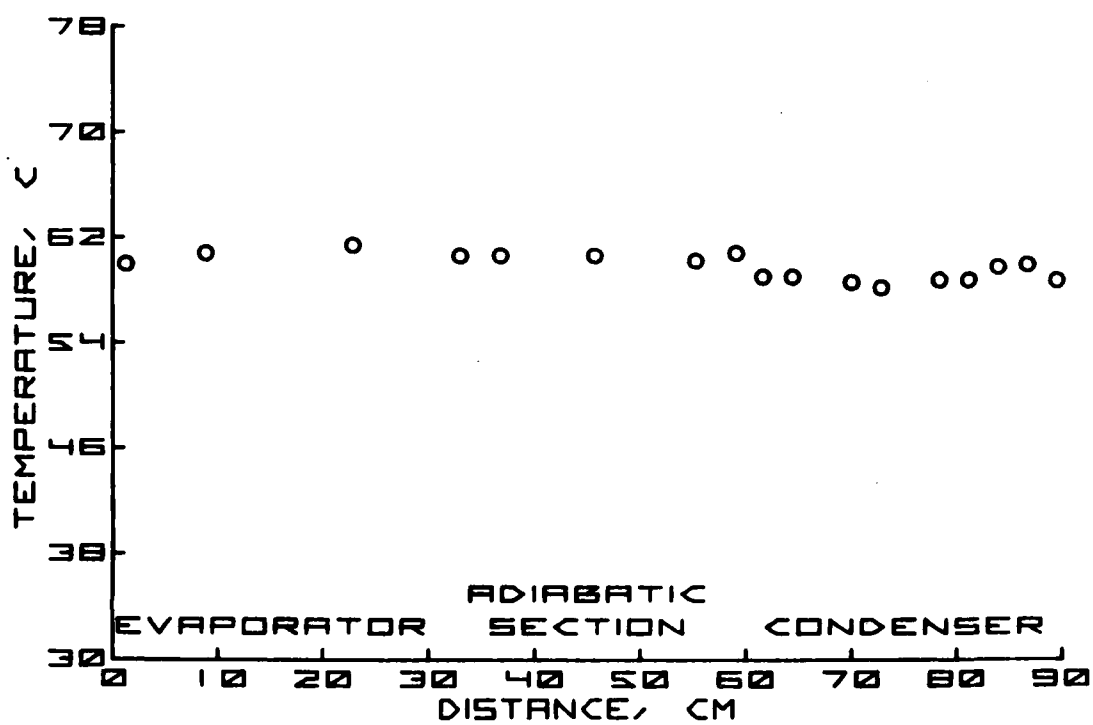


Figure 10.- A Normal Temperature Profile of a Well Behaved, Gas Free Heat Pipe.

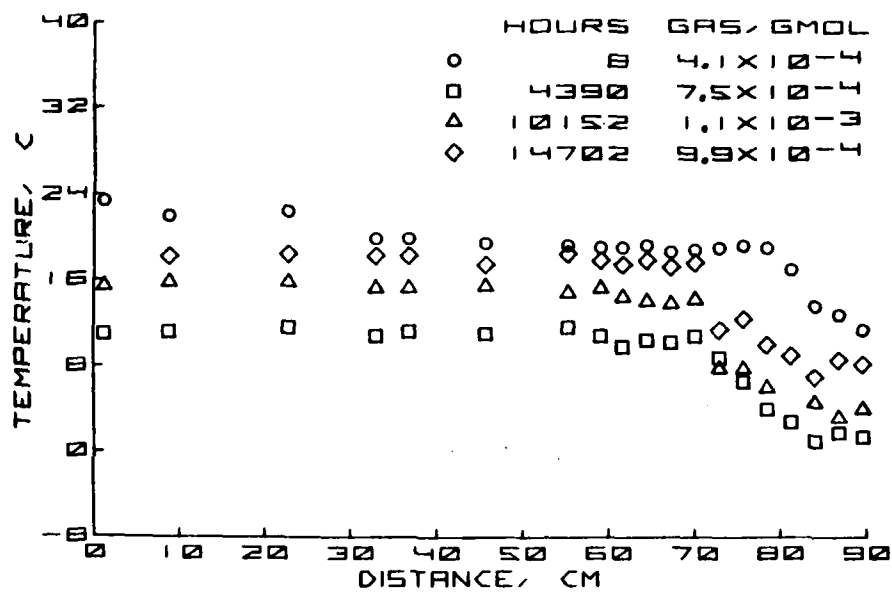


Figure 11. - Temperature Profiles for Pipe 10
Showing Evidence of Gas Accumulation with Time.

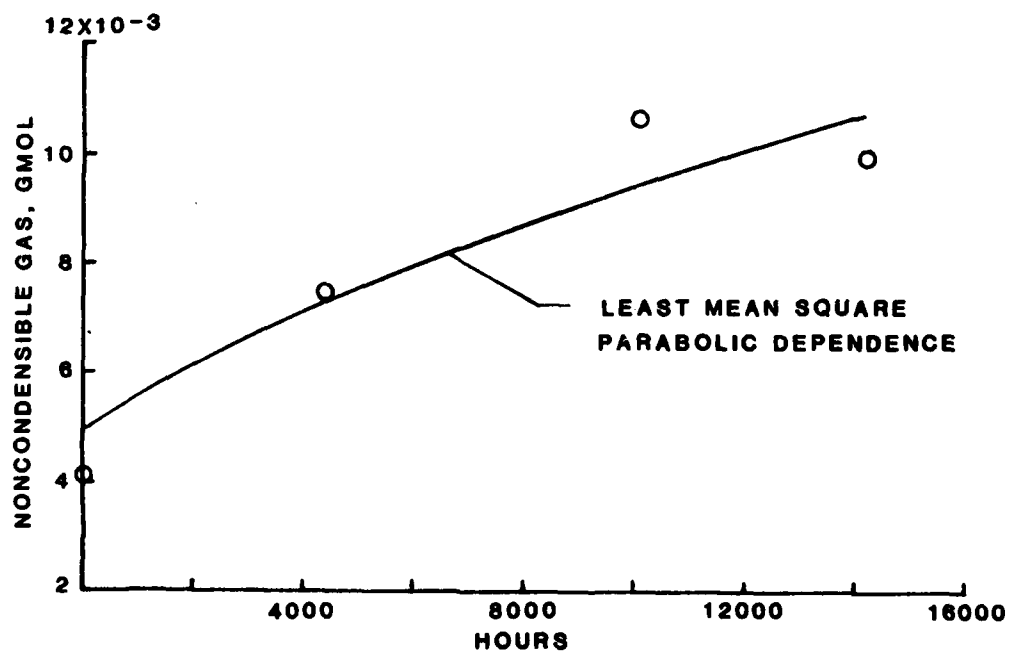


Figure 12. - Noncondensable Gas Against Life Test Time
for Pipe 10 from Data in Figure 11.

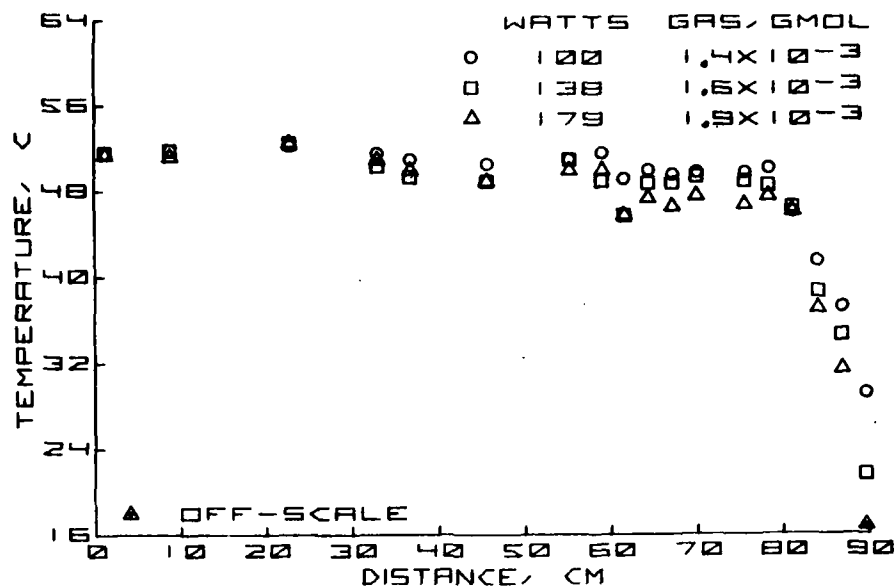


Figure 13. - Temperature Profiles for Pipe 10 Showing How Increasing Power Gives the Erroneous Appearance of Gas.

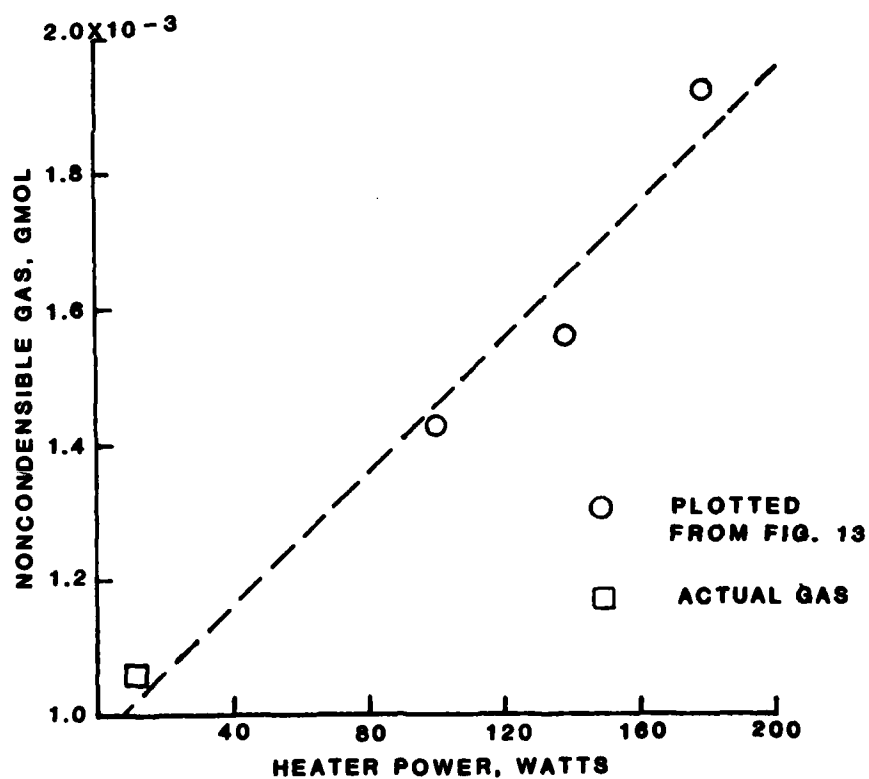


Figure 14. - Increase of Noncondensable Gas with Power for Pipe 10.

due to larger pressure difference across the vapor-liquid interface. This excess liquid in Pipe 10 seems to have accumulated in the condenser, augmenting the temperature profile caused by the noncondensable gas. From this plot, it is evident that gas accumulation data must be taken at low power.

Figure 15 gives a further illustration of how liquid accumulating in the condenser at higher powers and elevations can masquerade as gas. In this figure, profiles are shown for 50 and 80 watts, taken at an evaporator elevation of 2.5 cm with Pipe 2. A temperature profile of the same pipe at a power of 11 watts and elevation of 0.63 cm taken during a gas check is also shown, giving no evidence of gas in the pipe. The combined effects of power and elevation result in a sharp drop in the temperature at the end of the condenser which cannot be easily distinguished from non-condensable gas.

In Pipes 2 and 10, where displaced liquid gives the appearance of gas (Figures 15, 13) internal configuration is the same. The severity of the power and elevation effects may depend on the wicking structure design in the particular heat pipe being considered. It is possible that some interior configurations display more latitude than others in containing displaced or excess liquid.

PERFORMANCE

How evaluation and comparison of pipes can be made from the information which was gained in ground performance testing of the Lewis thermal control heat pipes will now be discussed. The maximum power which can be transported by the heat pipe under a specified set of conditions is the measure of performance. This maximum power is determined by such factors as pipe internal configuration, working fluid, length and elevation of the evaporator (when testing in a gravitational field). Envelopes of maximum power

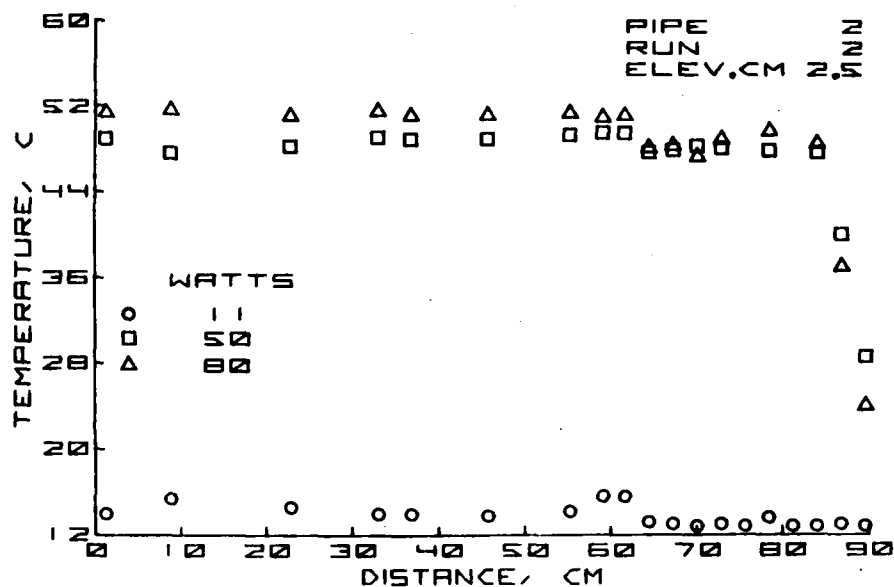


Figure 15. - Temperature Profiles for Pipe 2, a Gas Free Pipe, Showing How High Elevation and Increasing Power Give Appearance of Gas.

against elevation were presented for the 21 pipes in Reference 7.

The sensitivity of heat pipe performance to evaporator elevation is indicative of the care required in levelling a spacecraft assembly for ground qualification test. Also, estimates of maximum power transmission in zero "g" can be made by suitably extrapolating the curve of maximum power against elevation to offset the hydrostatic head in one "g".

The line of maximum power against evaporator elevation can be approached either by increasing elevation at constant power, or by increasing power at constant elevation. As mentioned in a previous section, both methods have been employed. Preference has been given to varying power, since the mechanical disturbance when elevation is changed may cause premature dryout.

Figure 16 illustrates the course of events when the evaporator of a heat pipe at constant power is elevated in steps. Data were taken on Heat Pipe 1 at a nominal adiabatic section temperature of 60° and increasing evaporator elevations. At an evaporator elevation of 0.6 cm (circles), the profile was essentially flat in the evaporator, adiabatic, and condenser sections. No evidence of noncondensable gas is seen, an observation substantiated for Pipe 1 by the gas checks (Reference 7). Elevation was then increased in steps until 3.2 cm (squares) was reached. The pipe was still transferring heat normally with a profile resembling that at 0.6 cm except that the temperatures near the end of the condenser section drop sharply. This could be misconstrued as gas, but, in reality, represents puddling of liquid due to the elevation. Subsequent elevation of the pipe to 3.8 cm resulted in dryout of the entire evaporator. The evaporator temperatures rose off scale while the adiabatic and condenser section temperatures fell sharply, showing that heat was no longer being transferred from the

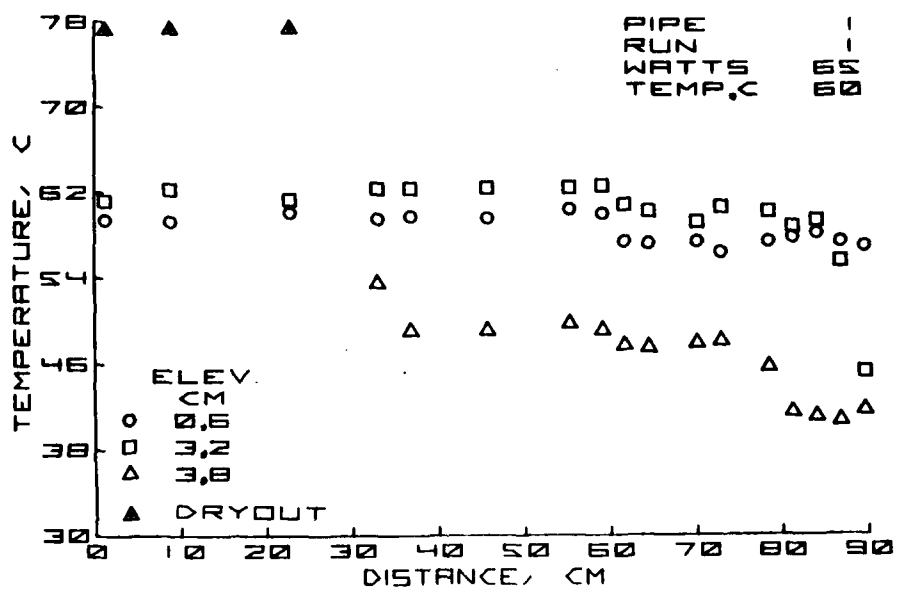


Figure 16. - Change in Temperature Profile with Elevation for Pipe 1, a Gas Free Pipe, Illustrating Evaporator Dryout.

evaporator. This profile represents an advanced stage of dryout. Frequently, in an earlier stage, only the first couple in the evaporator will be somewhat elevated.

When power is increased at constant elevation, the temperature profiles may resemble those in Figure 17. Pipe 16 was operated at several power levels to, and including, dryout, with no evaporator elevation. The temperature profile at 131 watts was essentially the same as any profile that might be taken at a lower power. At 140 watts, the first evaporator thermocouple was slightly elevated, suggesting partial dryout of the circumferential grooves in the vicinity of the couple. This represents a stable condition which can persist indefinitely. The temperature of the same couple at 147 watts was elevated further. Moreover, the state was unstable since rapid dryout of the entire evaporator ensued.

Some pipes could be dried out at no combination of power and elevation attainable in the Lewis facility. Figure 18 shows temperature against distance for Pipe 9 at an evaporator elevation of 3.8 cm, at three power levels. No clear evidence of dryout is observed. While the second evaporator thermocouple temperature was higher than the first, this is at best evidence of only a local deficiency in working fluid which did not propagate to an evaporator dryout. The temperature fall-off at the condenser end was probably due to the combined effect of a puddle and the small amount of noncondensable gas in this pipe. The nominal adiabatic temperature sought was 50°C , but the sink temperature could not be lowered sufficiently to maintain this. The temperature drop between the adiabatic and condenser sections was much greater than between the evaporator and adiabatic section. This suggests that the heat transfer coefficient was much smaller in the condenser than in the evaporator.

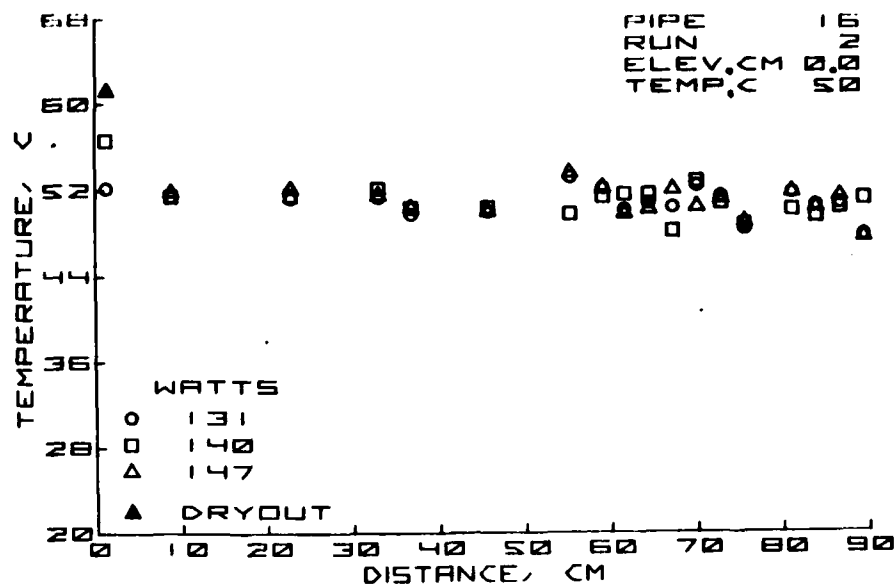


Figure 17. - Temperature Profiles for Pipe 16, a Gas Free Pipe, Showing the Onset of Dryout as Power is Increased.

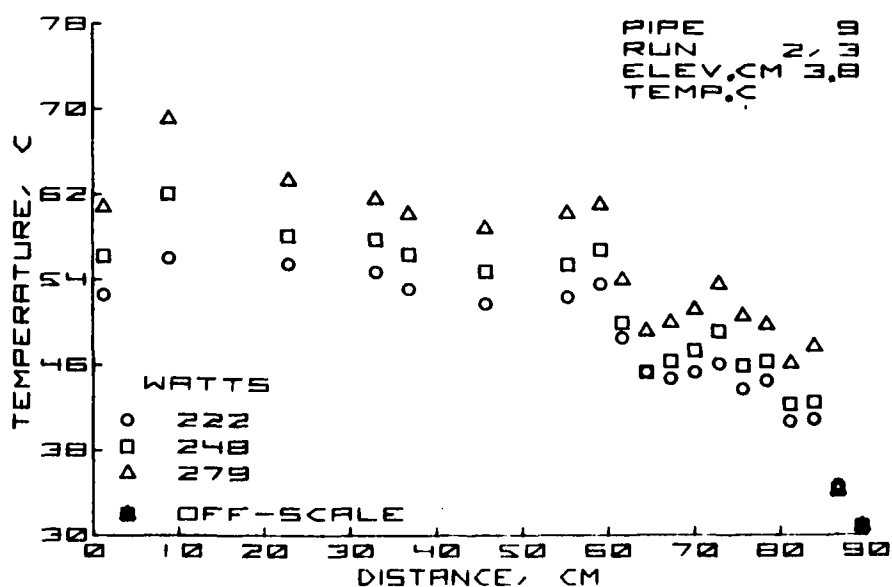


Figure 18. - Temperature Profiles for Pipe 9 Showing the Behavior of a Pipe Which Could Not be Dried Out as Power Was Increased.

PIPE PERFORMANCE VARIABILITY

For statistical purposes, three specimens of each type of heat pipe were tested in the program. As previously mentioned, considerable variation was found in noncondensable gas among members of a single group (Reference 7). Other investigators (Reference 7) have reported gas formation data for heat pipes in groups of three, ostensibly identical as to manufacturing and processing. Again, variation was found, with gas in two pipes frequently being similar, and the third having quite a different amount.

In some instances, heat transport capability may likewise be quite different for three pipes of a kind. Figure 19 shows temperature against distance for Pipes 16, 17, and 18 (Group I of Table 1), at an elevation of 1.9 cm. Pipes 16 and 17 experienced dryout at 81 and 60 watts, respectively. Pipe 18, on the other hand, could not be dried out at 1.9 cm elevation, nor indeed at any condition attainable in the facility. No evidence of noncondensable gas was found in the pipes of this group. Corrosive failure does not therefore appear to be a ready explanation for the wide spread in heat transfer capacity. Some variation in manufacturing tolerances thus appears a more likely explanation. Whether wide variations in performance, as well as in gas (References 6 and 7), is to be a common experience in spacecraft thermal control heat pipes remains to be seen.

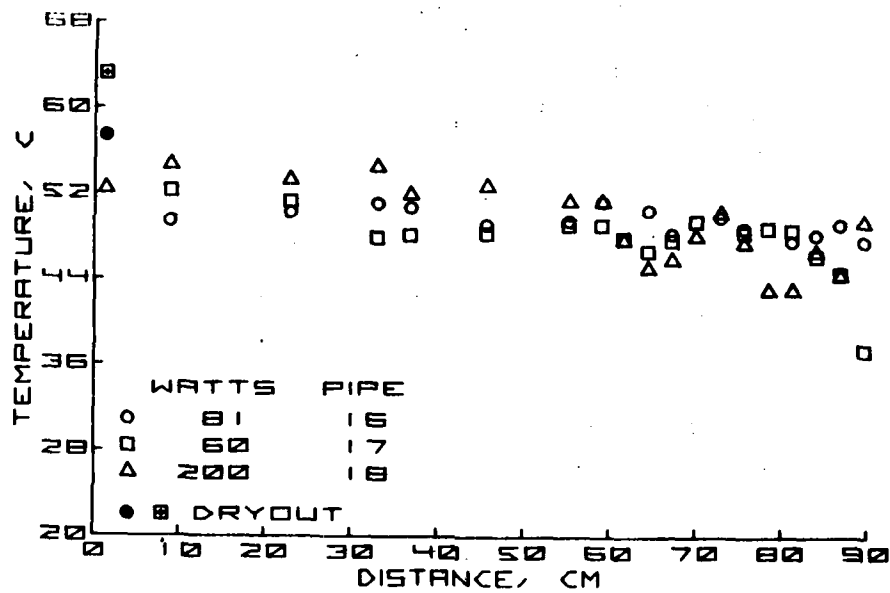


Figure 19. - Temperature Profiles for Heat Pipes of Group F Showing Variation in Heat Transport Capability within Pipes of the Same Group. Evaporator Elevation 1.9 cm.

SECTION IV CONCLUDING REMARKS

Results for a life test evaluation of spacecraft thermal control heat pipes conducted at the Lewis Research Center of NASA were published earlier. The present report has described in some detail the test facilities, data-taking equipment, testing procedures, data analysis methods, and means of interpretation which were employed. The false starts and difficulties encountered were enumerated in more detail than was possible in the earlier report. Particular attention has been devoted to the development of a satisfactory evaporator heater and to the problems overcome in thermocoupling the heat pipes. Also, the very successful procedures for acquiring, storing, retrieving, and plotting the large volumes of data generated have been described in depth. The intent has been to provide other experimentalists with sufficient detail on heat pipe life testing and performance evaluation to avoid some of the problems which were overcome in the previous program. Should facilities of the type described herein be employed in the future, the learning time for the project may thereby be shortened.

SECTION V

RECOMMENDATIONS

For the benefit of those setting up new heat pipe life facilities, or beginning new programs involving long-term life and performance testing, some specific recommendations are suggested here.

FACILITIES

Enclosure of the heat pipe in an evacuated housing was an effective way of minimizing thermal losses from the evaporator heater. However, removal and re-installation of the housing for inspection and repair of thermocouples proved to be a tedious chore. Alignment and levelling of pipes was required after much work. The facilities were designed with the possibility of testing cryogenic heat pipes, for which much isolation is necessary. Under the less stringent conditions of thermal control heat pipe testing, a simple insulated jacket may be adequate for many projects.

The heat extractor was an effective way to remove heat from the pipe. By segmenting the blocks and by using shrink plastic tubing beneath them, the axial wall heat conduction was greatly reduced. Sharp distinction could then be made between the active and gas-blocked parts of the condenser which aided the computation of noncondensable gas.

A matter to which insufficient attention was paid was the orientation of the longitudinal split in the heat extractor. In particular, with the slab wick of Configuration I (Figure 1) vertical, and with the heat extractor also vertical, the conduction path from the vapor space to the wall thermocouples in the split was through a thick fillet of liquid. This made the observation of vapor temperature less certain than it possibly needed to be.

Indeed, the wall temperature which was employed as the vapor temperature adjacent to a thermocouple may have reflected the influence of a liquid flowing from a region of different temperature.

Another matter which might require reconsideration is the routing of the coolant liquid through the heat extractor. The tubing was connected in such a way as to assure that the average temperature of the heat extractor was constant the entire length of the condenser. However, the opposing blocks on the two sides of the longitudinal split were at different temperatures. The consequence of this was circumferential heat conduction in the wall of the heat pipe itself. By a simple reconnection of the coolant tubes, at each end of the extractor, the blocks on both sides of the longitudinal split also can be made to operate at the same mean temperature.

The radiation heaters employed at the outset had serious shortcomings, as mentioned. The greased sleeve which converted the heater to the conduction mode was quite successful. All evidence suggests that the grease distribution was uniform. However, further assurance of uniformity could be ascertained by careful placement of grease fittings, or other stratagems.

Difficulty was encountered in obtaining vacuum-tight sealing of insulated thermocouple wire in feed-thrus. To avoid this, vacuum feed-thrus with sealed conducting pins could be considered, but then spurious voltages associated with temperature difference and material difference on the two ends of the pin would require attention.

The single circulating cooling system using a single coolant pump was satisfactory for maintaining the steady life test temperature. This homemade system could be replaced with several commercial laboratory-type temperature baths which provide a pump for coolant circulation. The advantages could be lower overall cost,

greater flexibility, and more precise temperature control. Conceivably, such baths could be used for maintaining both life test temperature and for establishing the low temperatures required for gas and performance checks. However, several heat pipes would then be subjected to low coolant temperatures while only one was being tested. Because the cooling capacity of the bath falls sharply with temperature, the operator would be confronted with adjusting and monitoring several pipes in addition to the one under test. The use of a single small bath cooling a single pipe during gas, or performance checks, as done in the program described here, still appears best. A lower gas check temperature might be considered in order to improve the accuracy of gas determinations.

INSTRUMENTATION AND DATA TAKING

The number and placement of thermocouples on the heat pipe were satisfactory. As mentioned above, consideration should be given to avoiding large liquid reservoirs and channels when locating thermocouples. A selector switch on each pipe placed parallel with the voltmeter scanner and the video bargraph, enabling single couples to be read for diagnostic purposes, proved very advantageous.

The use of thermally conducting epoxy cement to hold the thermocouple beads in place on aluminum pipes was a great convenience. The tacit assumption was made that the temperature was being determined at the outer wall of the pipe. It would be desirable for future installations to study the method of placement of thermocouples where glued attachment is necessary, and to develop a protocol which results in precise control of the attachment.

The data taking and retrieving system proved quite satisfactory for the time period in which it was purchased. A system with similar software control functions could be considered today, implemented with modern computer hardware.

DATA TAKING PROCEDURES

A review of the recorded data suggest that more frequent determinations of noncondensable gas would have benefitted the statistics of the study. On the other hand, only infrequent performance checks are necessary. Certainly a check at the beginning of testing is required. The frequency thereafter should be determined by the amount of damage indicated by the observed noncondensable gas formation.

The video bargraph proved invaluable for quick daily monitoring of the status of the heat pipes. The instant camera photographs of the data-taking events provided a qualitative record that backed up the taped data.

A study of possible periodic temperature fluctuations at supposedly steady-state conditions should have been performed. Some thermocouple readings, dismissed as erroneous, may have been the result of viewing a periodic phenomenon at a single point in time. The entire data sweep of a heat pipe consumed about one second. Perhaps a multiple sampling and averaging of each thermocouple during a longer sweep would have given better results.

OTHER TECHNIQUES OF LIFE TESTING

A radical suggestion is made at this point concerning the conduct of future life tests. The decomposition reactions are probably influenced more by temperature than pumping action of the pipe. If this is the case, the pipes could be stored en masse in a controlled environment box at the desired life test temperature. A small temperature gradient in the box would ensure at least minimum heat pipe action during the accrual of life test time. A single gas and performance test rig could then be designed to accommodate each pipe individually, in succession, for the periodic checks.

Proceeding further, perhaps short-term gas generation tests in such an environment could be correlated with long-term life tests of the type described in this report. If such were the case, pipes intended for flight service could be screened to eliminate the potentially bad ones prior to assembly in spacecraft. This might lessen the amount of processing required in assembly, which sometimes leads to ambiguous results anyway. It could also diminish the amount of redundancy required in design of the heat rejection system.

APPENDIX
THE DATA SYSTEM, DATA ACQUISITION FUNCTIONS,
DATA RETRIEVAL FUNCTIONS AND
GAS COMPUTATION

THE DATA SYSTEM

The following components and options were used by the data system for data retrieval:

9810A Calculator with Option 001 (111 total data storage registers), Option 003 (2036 total program steps), and Option 004 (printer); 9865A Cassette Memory; 3480C Digital Voltmeter with 3485A Scanning Unit containing Option 001 (41 channels).

Also required were the following read-only memory blocks which plug into the 9810A calculator:

11213A User Definable Functions Block; 11261A Plotter/Printer Alpha Block; 11262A Peripheral Control/Cassette Memory Block. For data retrieval, plotting and analysis, the calculator and cassette memory were again in service, a 9862A Calculator Plotter was employed, a 11210A Mathematics Block replaced the user definable block, and the voltmeter/scanner unit was not in service.

The following interface cables were required between the calculator and the peripherals stated:

to the 9862A Plotter, the Signal Cable, part number 09862-60441; to the 3485A Scanning Unit, the 11202A TTL/IO Interface; from the 3480C Voltmeter, 11203A BCD Input Interface. These items plugged into slots in the rear of the 9810A Calculator.

Prior to data taking, the switches on the scanner face were set to the following positions: Filter, REM (remote); Range, REM (remote); Channel Delay, NONE; Mode, REMOTE; Random/Last Channel, 41 (two switches). With power on to the voltmeter buttons, HOME and INITIATE were pressed on the scanner face.

DATA ACQUISITION SYSTEM

The data-taking functions provided by the user-definable keys of the 9810A Calculator when programmed with the Take-Data program were as follows:

Function	Name	Key
f_1	READ POWER	C
f_2	TAKE DATA	D
f_3	SWEEP ALL TEMPERATURES	E
f_4	COLD JUNCTION	H
f_5	PRINT DATA	I
f_6	READ ONE TEMPERATURE	J
f_7	DELETE DATA	M
f_8	RECORD DATA	N
f_9	IDENTIFY TAPE	O

Functions f_2 , f_7 , f_8 , and f_9 were interlocked to prevent mishaps or out of sequence operation. The initiating function was f_9 IDENTIFY TAPE. No data could be taken until this function verified that the cassette tape in use was correct for the heat pipe under test. Data could then be taken into the calculator and arranged for recording using f_2 TAKE DATA. Deletion of bad data was done by f_7 DELETE DATA. The function f_8 RECORD DATA, located the proper file on the data tape, recorded data, and reset some of the control counters for functions f_2 , f_7 , and f_9 . The remaining functions could be used by the operator at will to check power and thermocouple readings for control purposes during data taking. Flow charts showing the structure of the major functions f_2 TAKE DATA, and f_9 IDENTIFY TAPE, are presented in Figures 20 and 21, respectively. Some of the mnemonics printed out by the calculator appear strange. The calculator keys calling the functions could only be used for this purpose, and were unavailable for

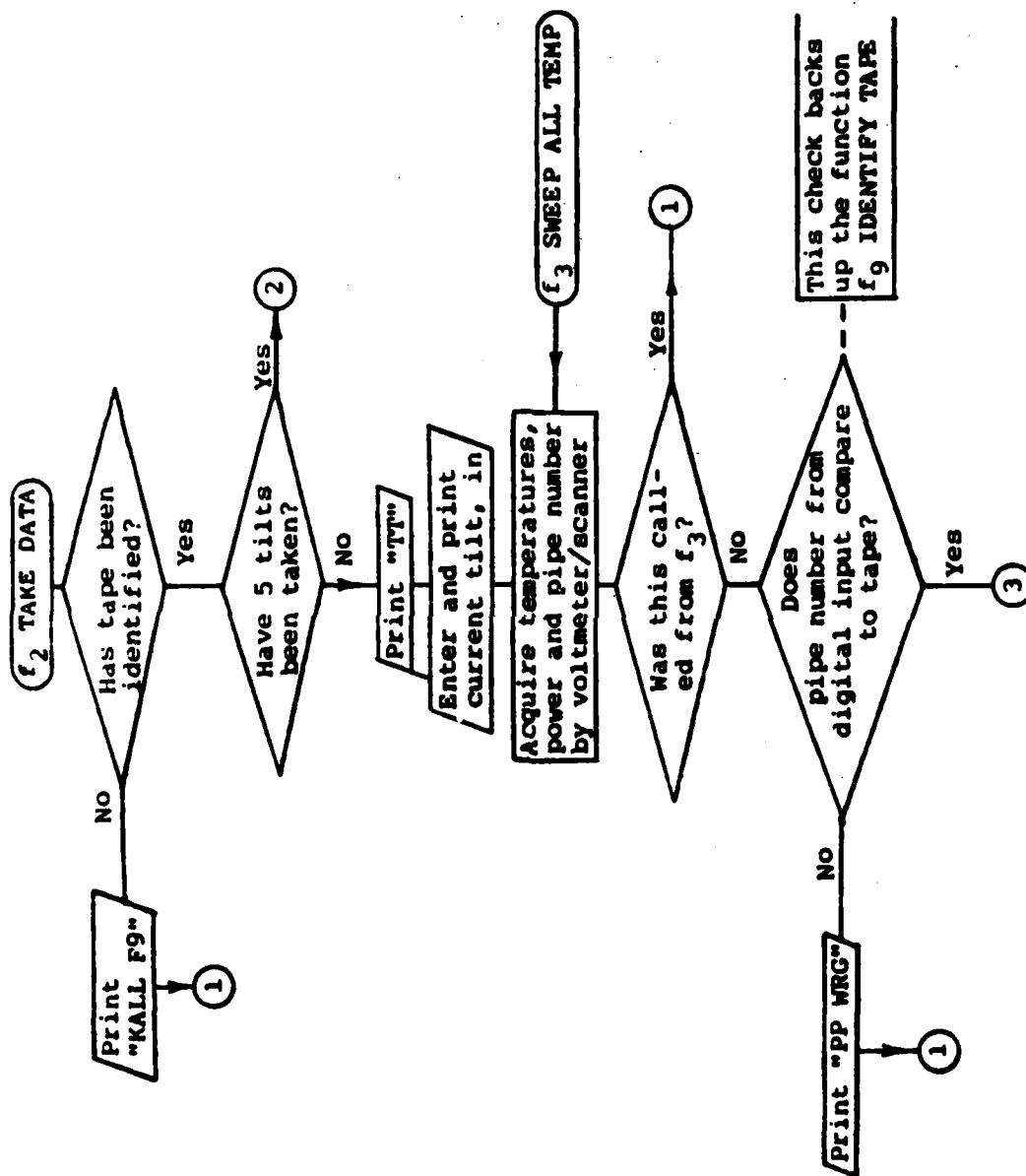


Figure 20. - Flow Chart for f_2 TAKE DATA.

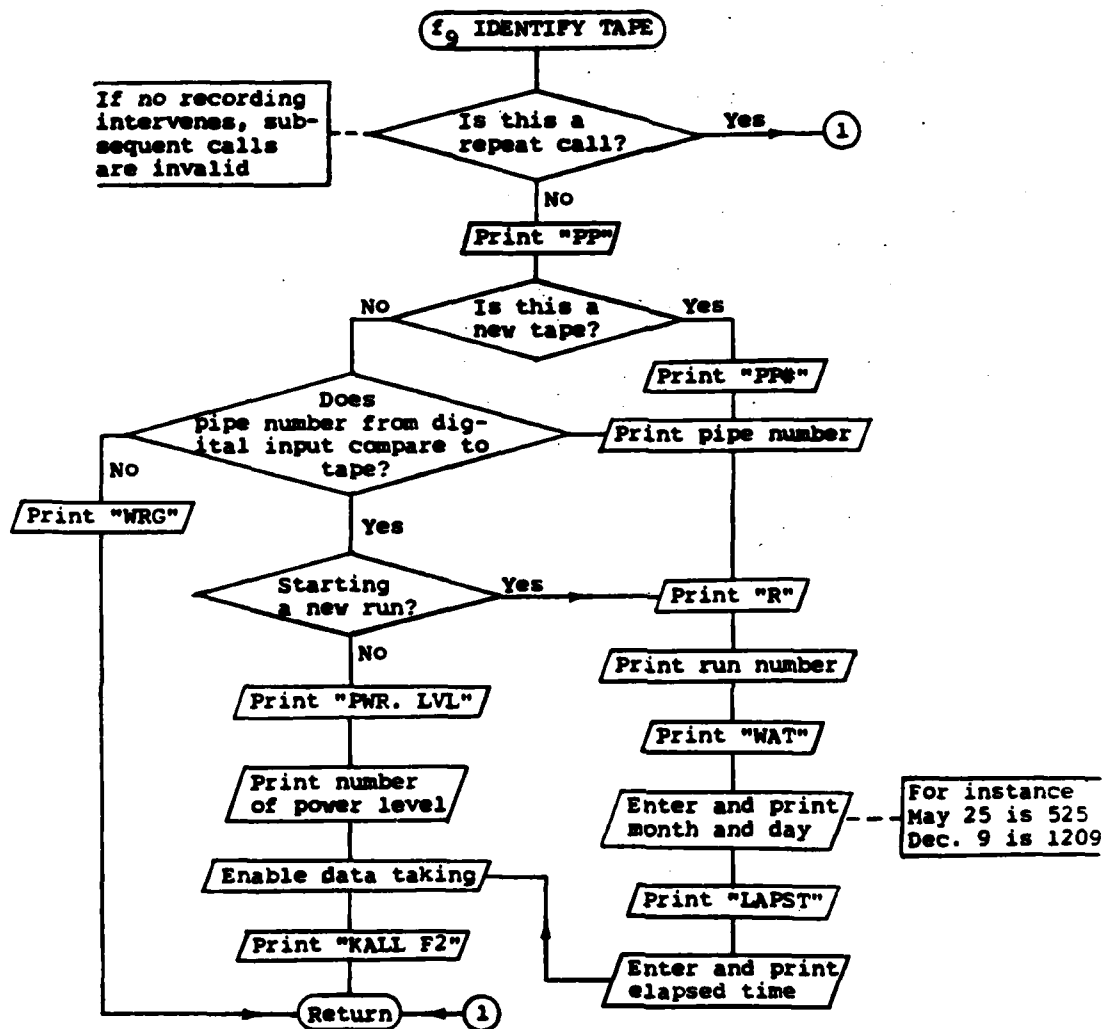


Figure 21. - Flow Chart for f₉ IDENTIFY TAPE.

alphabetic printing. Adaptation of the data-taking functions to more modern machines of larger capacity would remove this restriction and permit the use of more explicit video, or printed instructions.

DATA STORAGE FORMAT

Prior to taking data, a cassette tape previously marked with a Mark-Tape program was inserted into the Cassette Recorder. The tape required was the one dedicated to the heat pipe into which the voltmeter/scanner was plugged. Software interlocks in the Take-Data Program prohibited wrong tapes from being used.

The tapes were marked for data storage into RUNS. Each RUN was divided into five POWER LEVELS and each POWER LEVEL in turn was divided into five TILTS. A pictorial representation of data storage on tape can be typified as follows:

RUN	10										11
POWER LEVEL	1		2			3.....5					1
TILT	1	2	3	4	5	1	2	3	4	5	1

The data storage format did not constrain data taking to the extent implied by the terminology. For each data-taking event, or TILT, heater power and all other required data were recorded and stood alone as a single data-taking event. Thus, power as well as pipe elevation could be varied from one TILT to another. However, date and elapsed time were recorded only at the beginning of each run, so a manual log was required for this information since a run extended over a period of time.

In anticipation of a larger volume of data than has yet been acquired, the data was greatly compacted before recording. The data register in the 9810A calculator permits far greater precision than was required for the

experimental data being acquired. The calculator displays a 10 digit mantissa and 2 digit exponent so a number from $+ 10^{-98}$ to $9.99999999 \times 10^{98}$ might be displayed. This afforded the opportunity for great savings on cassette tapes. The data acquired at each TILT were as follows:

power, watts
 tilt or elevation, inches
 cold junction temperature, $^{\circ}\text{C}$
 pipe number, 1 through 31
 thermocouples 1
 2
 .
 .
 .
 .
 27
 28

The data for a single TILT record were stored in groups of four to a data register, to occupy eight data registers:

reg. 1	power	tilt	cold junction	pipe number
reg. 2	T_1	T_2	T_3	T_4
.			.	
.			.	
.			.	
.			.	
reg. 8	T_{25}	T_{26}	T_{27}	T_{28}

This format imposed the following ranges and rounding on stored data:

Power 10 to 998 watts, to nearest watt
 Tilt -1.5 to + 1.99 inches
 Cold junction temperature 1 to 99.8°C
 Pipe numbers 1 to 32
 Thermocouple temperatures 1 to 99.7°C
 rounded to the nearest 0.2°C

For example, if four thermocouple readings had been taken and converted to the following temperatures:
 69.16....°C, 23.36....°C, 6.52....°C, 49.84....°C,
 these would have been stored in a single data register in scientific notation as 6.922340664 98. Open thermocouples, temperatures exceeding 99.7°C, and temperatures less than 1°C were coded to be retrieved as 99.8°C. The calculator was programmed to ignore such values or to plot them with a warning code at the time of retrieval.

In addition to the data acquired at each TILT, the following information was recorded in a file at the beginning of each new run by function f₉ IDENTIFY TAPE:

run
 date
 hours of operation

These were stored in a single data register:

2 . 0 6 0 3 0 0 1 2 3 1 2
 run 2 June 3 12,312 hours

DATA RETRIEVAL, PLOTTING, AND COMPUTATION

Plot-Data programs were written to recall and plot data stored on the cassette tapes. Examples of plots produced by these programs have been presented in the main body of this report. The Gas-Analysis-programs also compute the noncondensable gas inventory for either ammonia-filled or methanol-filled pipes. Use of a Gas-Analysis program will be illustrated here.

Prior to plotting, blank graph paper is ruled by one of several Draw-Grid programs, with a choice of spaces for lettering. The Gas-Analysis program and coordinates of the thermocouples are entered into the calculator from cassette tapes or magnetic cards. The cassette tape containing data for the heat pipe to be analyzed is placed in the cassette recorder and execution is begun. The calculator prompts

the operator for keyboard input by printing out instructions, kept brief to save calculator memory. Resumption of operation after each keyboard entry is made by pressing the run key, labeled CONTINUE, on the 9810A calculator.

A flow chart for one version of the Gas-Analysis program is shown in Figure 22. In the version charted, three choices of Y-axis scale, all having a span of 48°C, can be selected from the keyboard by entering a code. In another version, any Y-axis scale can be obtained, from a minimum of -9°C to a maximum of 99°C, provided that the span is 48°C.

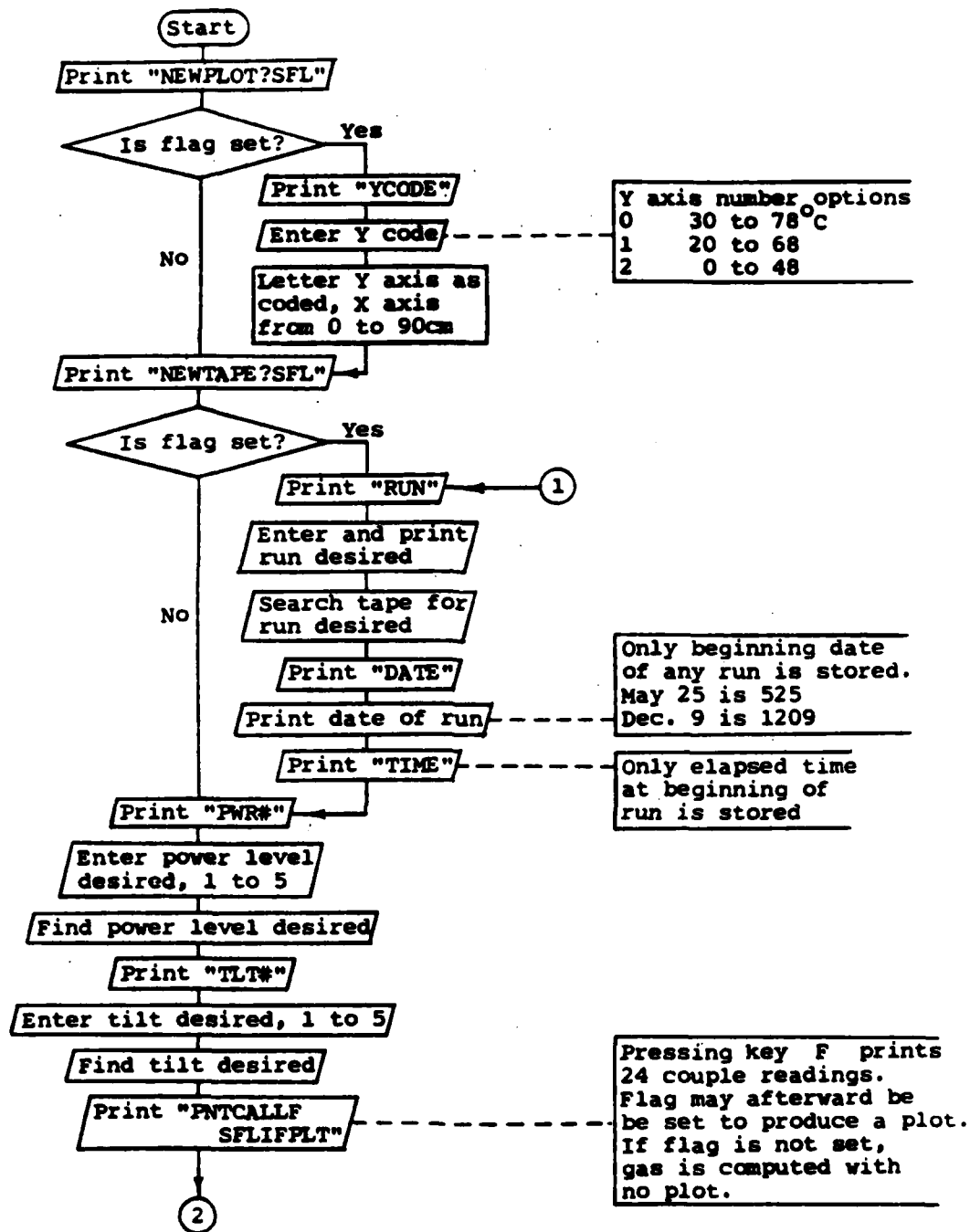
The printout created when a plot similar to Figure 11 was executed is shown in Figure 23. The printout has been briefly annotated to aid interpretation.

The moles n of noncondensable gas were computed in the Gas-Analysis program from the thermocouple readings by the ideal gas law using the equation (Reference 7):

$$n = \sum_{i=i_f}^N \frac{P_{ad} - P_{vi}}{RT_i} A_v L_b$$

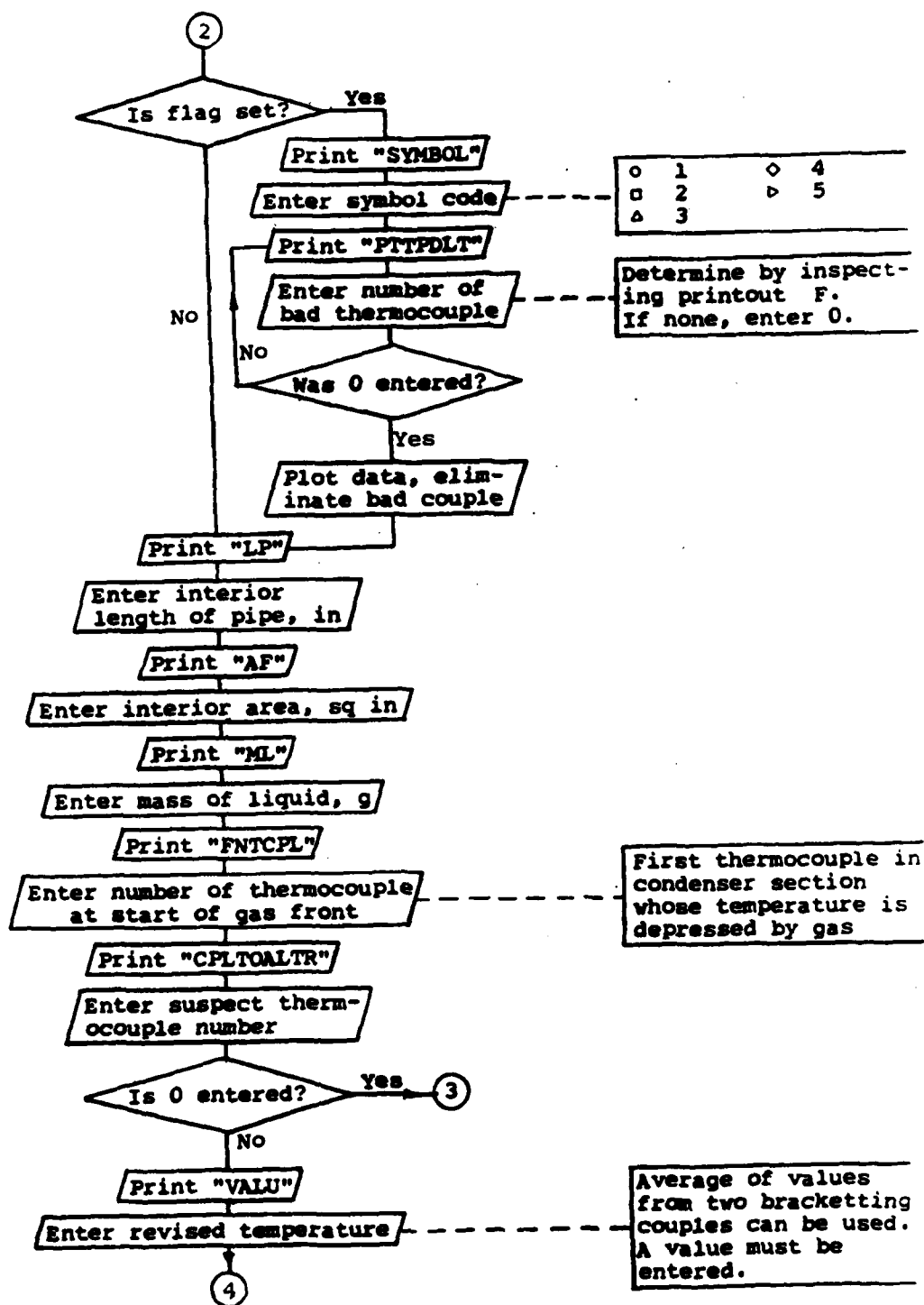
where:

A_v	vapor cross section area of pipe
i	thermocouple number
i_f	number of first couple showing gas
L_b	distance from one condenser block to next, center to center
N	total number of thermocouples used in the calculator
P_{ad}	vapor pressure at the mean adiabatic temperature
P_{vi}	working fluid vapor pressure at T_i
R	gas constant
T_i	absolute wall temperature at thermocouple i



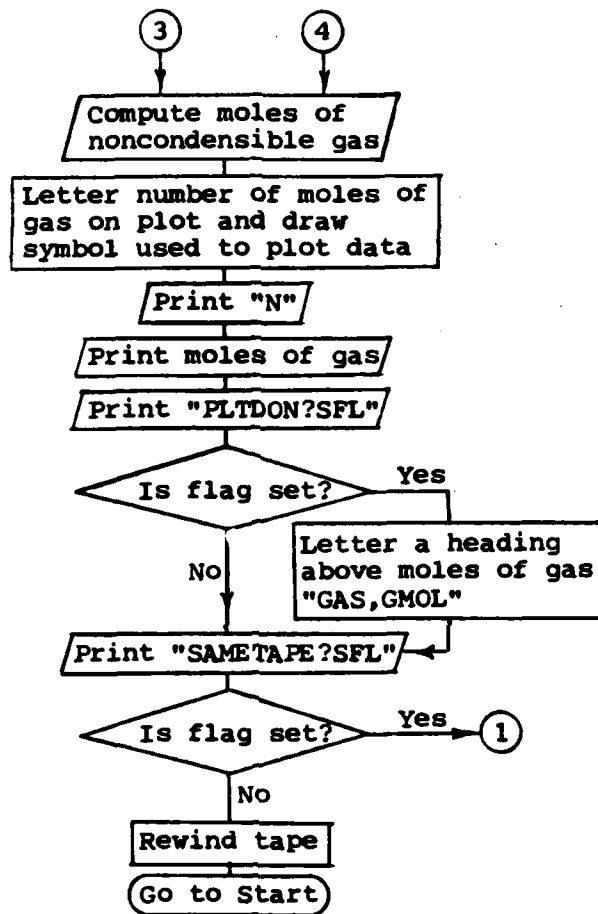
(a) Start

Figure 22. - Flow Chart for Gas Analysis Program.



(b) Continuation

Figure 22. - Flow Chart for Gas Analysis Program.



(c) Conclusion

Figure 22. - Flow Chart for Gas Analysis Program.

NEWPLOT^SFL	Flag was set	(Continuation)	
YCODE?		SMSLE	Flag set after print
2.0	Range, 0 to 48°C	1.	Choose circle symbol
NEWTAPE^SFL	Flag was Set, Pipe 10	PNTTODLT	18.0 Couple 18 deleted from
RUN			plot
4.	Run 4 selected	PNTTODLT	0. No more points deleted
DATE	Nominal date Aug. 9		points are plotted
809.	when run started	LP	35.630000 Pipe length, in
TIME	Actual date Oct. 25	AF	0.143150 Inside area of pipe
12408.	and time 14 223 hrs	ML	18.500000 Mass of liquid, gm
PWR0	Power was 11 watts	FNTCPL0	18.0 Front couple is
4.0	from logbook		designated as 18
TLT0	Tilt or elevation was	CPLTOALTR	18.0 Choose couple 18
2.0	0.63 cm from logbook		to alter
PNTCALLF	Function F printed	VALU	13.10 Value chosen for 18 is
SFLIFPLY	out the thermocouples		mean of 17 and 19
1.	Thermocouple number	CPLTOALTR	No further alterations
18.2	Couple temperature	N	1.060303569-03 Compute gas, gmol
2.		PLTDON^SFL	Plot not done, no flag
99.0	Couple 2 was not used	SAMEAPE^SFL	New tape, no flag
3.		NEWPLOT^SFL	Same plot, no flag
99.0	Not in use	NEWTAPE^SFL	Pipe 11, flag set
4.		RUN	
99.0	Not in use	3.	
5.		DATE	0.
18.2		TIME	14203.
6.		PWR0	1.0
99.0	Not in use	TLT0	2.0
7.		PNTCALLF	
18.0		SFLIFPLY	
8.		1.	
99.0	Not in use	15.4	
9.		2.	
17.6		99.0	
10.		3.	
17.4		99.0	
11.		4.	
18.0		99.0	
12.		5.	
13.		17.4	
18.2		6.	
14.		99.0	
17.2		7.	
15.		15.0	
17.4		8.	
16.		99.0	
16.0		9.	
17.		16.4	
16.0		10.	
18.		10.4	
9.0	Plot shows couple 18 to	11.	
19.	be at gas front, but	17.4	
10.2	value appears bad	12.	
20.			
0.6			
21.			
7.0			
22.			
6.4			
23.			
0.0			
24.			
7.4			

Figure 23. - Calculator Printout Produced during Execution of the Gas Analysis Program.

The temperature indicated by the thermocouples on the exterior wall of the heat pipe were taken as the temperatures of the vapor in the center of the duct. For both the adiabatic section and the completely gas-blocked part of the condenser, this is a good assumption. In the vicinity of the gas front, however, heat transfer causes the wall temperature to be less than the mean vapor temperature at the same cross section. The expression above will give a value of n which is larger than the actual value.

A simple means of estimating the true vapor temperature in the gas front region was employed in Reference 6. In a typical case reported there, the gas inventory was 6% less using the corrected vapor temperature than when the wall temperatures were employed. Because of limited memory, such a correction could not be conveniently employed with the data from the Lewis pipes.

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